Renewable and Sustainable Energy Reviews 24 (2013) 514–533

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A global comparative review of biodiesel production from *jatropha curcas* using different homogeneous acid and alkaline catalysts: Study of physical and chemical properties

A.S. Silitonga [a,b], H.H. Masjuki [a], T.M.I. Mahlia [c], H.C. Ong [a,*], A.E. Atabani [a], W.T. Chong [a]

[a] *Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[b] *Department of Mechanical Engineering, Medan State Polytechnic, 20155 Medan, Indonesia*
[c] *Department of Mechanical Engineering, Universiti Tenaga Nasional, 43000 Kajang, Selangor, Malaysia*

A R T I C L E I N F O

Article history:
Received 5 July 2012
Received in revised form
4 March 2013
Accepted 15 March 2013
Available online 27 April 2013

Keywords:
Jatropha curcas
Homogeneous acid and alkaline catalyst
Esterification
Transesterification
Free fatty acid
Physicochemical property

A B S T R A C T

Recently, *jatropha curcas methyl* ester (biodiesel) as a potential substitute to petrol diesel has prompted many researchers around the world to carry out extensive investigation. This is because *jatropha curcas* oil is non-edible that can be easily grown in a harsh environment and the seeds of *jatropha curcas* fruit contain 40–60% oil. In this study, free fatty acid profile of *jatropha curcas* oil has been determined and compared with literature studies. It is found that *jatropha curcas* mainly contains 13.0% palmitic acid, 44.5% oleic acid and 35.4% linoeic acid. Moreover, *jatropha curcas* biodiesel was produced using different acid catalysts (HCL and H_2SO_4) and alkaline catalysts (NaOH, KOH, CH_3ONa and CH_3OK). The properties of produced *jatropha curcas* methyl esters such as viscosity, density, flash point, cloud point, pour point, calorific value, acid value, iodine value, condradson carbon residue and sulfate ash have been determined and analyzed. Overall, the properties of *jatropha curcas* biodiesel were in the range which could be accepted and have met ASTM D6751 and EN 14214 standards.
© 2013 Elsevier Ltd. All rights reserved.

Contents

Abbreviations: AIME, *Azadirachta indica* methyl ester; CJCO, crude *jatropha curcas* oil; JCME, *Jatropha curcas* methyl ester; JCB, *Jatropha curcas* blending; PPME, *Pongamia pinnata* methyl ester; RCME, *Ricinus communis* methyl ester.

* Correspondence to: Department of Mechanical University Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
E-mail addresses: ardinsu@yahoo.co.id (A.S. Silitonga), ong1983@yahoo.com (H.C. Ong).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.03.044

1. Introduction

Increasing population and energy consumption have surged continuously in the world due to high standard of living especially after the inauguration of the industrial revolution in 20th century. As a result, the world is confronted with the fossil fuel resource running out and also environmental degradation [1,2]. Moreover, high oil prices and rapid economic growth has led to many efforts being done to establish sustainable development programs and support national researches in renewable energy such as biofuel, solar, wind etc. The edibles oil as first generation feedstock due to the high biodiesel yield and easy processing with low free fatty acid content [3–6]. Currently, soybean and rapeseed (edible oil) are considered as biodiesel feedstock and produced in US and European countries because they have surplus of those feedstock. However, palm oil has dominant biodiesel feedstock in South East Asian countries such as Indonesia, Malaysia and Thailand. On the other hand, edible oil as biodiesel feedstock has raised concerns such as fuel vs. food issue and environmental problems with serious destruction of vital soil resources and deforestation [1,7,8]. All of these factors have negatively affected the economic viability of biodiesel production from edible oils. Therefore, the exploration of non-edible crops and the utilization of by products in the biodiesel production may significantly reduce the cost of biodiesel especially in developing countries which can hardly afford the high cost of edible oils. Biodiesel is defined as monoalkyl esters of vegetable oils, animal fats and waste cooking oil produced through the transesterification process [9–13]. It is eco-friendly, biodegradable, renewable, and non-toxic compared to petrol diesel [14–17]. Moreover, the feasibility of non-edible oil especially *jatropha curcas* is economically compare to edible oil feedstock [8,12,15,18–21]. Thus, *jatropha curcas* as second generation feedstock has been promising to substitute petrol diesel due to the availability, sustainability and lower feedstocks price in the market [22,23].



Native : Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama

Exotic : Angola, Antigua and Barbuda, Argentina, Bahamas, Barbados, Benin, Bolivia, Brazil, Burkina Faso, Cambodia, Cameroon, Cape Verde, Central African Republic, Chad, China, Colombia, Cote d'Ivoire, Cuba, Democratic Republic of Congo, Dominica, Dominican Republic, Ecuador, Egypt, Eritrea, Ethiopia, French Guiana, Gabon, Gambia, Ghana, Grenada, Guadeloupe, Guinea, Guinea-Bissau, Haiti, India, Indonesia, Jamaica, Japan, Kenya, Laos, Liberia, Madagascar, Malawi, Malaysia, Mali, Martinique, Mauritania, Montserrat, Mozambique, Myanmar, Namibia, Nepal, Netherlands Antilles, Nigeria, Peru, Philippines, Portugal, Puerto Rico, Sao Tome et Principe, Senegal, Sierra Leone, Somalia, South Africa, Sri Lanka, St Kitts and Nevis, St Lucia, St Vincent and the Grenadines, Tanzania, Thailand, Togo, Trinidad and Tobago, Uganda, US, Venezuela, Vietnam, Virgin Islands (US), Zanzibar, Zimbabwe

Fig. 1. The distribution of *jatropha curcas* L. plants around the world [35].

1.1. *Botanical description of jatropha curcas L.*

The name *jatropha* is derived from latin words *jatros* (doctor) and *trophe* (food) as it has many medicinal values [24–26]. *Jatropha curcas* L. is a small tree or large shrub up to 5–7 m tall belonging to the Euphorbiaceae family. The plant has an average life span of up to 50 years [15,27]. *Jatropha curcas* is native to Mexico, Central America, Africa, India, Brazil, Argentina and Paraguay [8,25,28,29]. It is well adapted to semi-arid conditions and more humid environmental conditions result better crop performance. The *jatropha curcas* plant is drought-resistant and has the capability to grow on marginal soils. It is a hardy and highly adaptable crop that can grow in marginal soils and capable to reclaim wasteland [30]. The fruit is a kernel which contains three seeds each. However, the production of the *jatropha curcas* seed yield ranges from 0.1 to 15 t/ha/year in different countries and regions [4] and the *jatropha curcas* oil yields is reported to be 1590 kg/ha/year [4,8,15]. Depending on variety, the oil content of decorticated seed ranges from 30% to 50% by weight and the kernel ranges from 45% to 60% [4,8,9,15]. However, the seeds of *jatropha curcas* are toxic to humans and animals [8,9,25,26,28]. The cultivation of *jatropha curcas* for the oil bearing production fruits is considered the first production step towards biodiesel production but the seeds can be used for many purposes such as lighting, lubricant soap and biomass elements [8,9,25,26,29,31,32]. The fatty acid composition of *jatropha curcas* is classified as linoleic or oleic acid types, which are unsaturated fatty acids [4,8,9,14,33,34]. The potential areas of *jatropha curcas* were distributed around the world is presented in Fig. 1 [35]. The fruit *jatropha curcas* fruit, shells, seeds and kernel are shown in Fig. 2.

1.2. *Objectives of this study*

To the best of the author's knowledge, no studies have been conducted yet to compare the physical and chemical properties of biodiesel produced from *jatropha curcas* using different acid and alkaline catalysts. Therefore, the aim of this paper is to study the biodiesel production from *jatropha curcas* using homogeneous acid (H_2SO_4 and HCL) and alkaline catalysts (NaOH, KOH, CH_3ONa and CH_3OK) followed by a detailed study of physical and chemical properties of the produced *jatropha curcas* methyl ester (JCME). Moreover, the results obtained in this study were compared with the previous findings in recent publications to give better insight into the properties of biodiesel produced from this feedstock.

2. Literature review for *jatropha curcas* biodiesel production

The quality of crude *jatropha curcas* oil (CJCO) deteriorates steadily as a result of inappropriate handling and storage condition. This will not only increase the water content but when the oil is exposed to air for long time, it will increase the percentage of free fatty acid significantly. The free fatty acid amount of CJCO will vary and depend on the quality of feedstock. It is believed that free fatty acid and water content have significant effects on the transesterification of CJCO [12,18,22]. It has been reported that CJCO has high free fatty acids content ($>1\%$) and consequently fail to convert directly to biodiesel using alkaline catalyzed transesterification process. This is because free fatty acid can react with alkali catalyst to form soaps; resulting in serious emulsification which leads to gel formation, extreme products separation problems and increases in the viscosity of biodiesel. Therefore, two-step transesterification process is one of the best and efficient methods that has been used globally to transesterify crude *jatropha curcas* oil that contains high free fatty acid. Acid catalyzed transesterification is often chosen when there is a high amount of free fatty acid content in the oil. Normally, an acid catalyst is used to reduce the amount of free fatty acid content to less than 1% by converting them into esters (esterification reaction). Then, an alkaline catalyst would be used in the second step to transesterify the triglycerides in *jatropha curcas* oil into biodiesel. Utilization of acid and alkaline catalysts in the first and second stage would help to overcome the problems of slow reaction rate with acid catalyst and eliminate the soap formation by using alkaline catalyst.



Fig. 2. Photo of *Jatropha curcas* L. fruit, shells, seeds and kernel.

Moreover, it has been observed that esterification reaction stops many times due to the effect of water produced when free fatty acid react with methanol to form esters [12,18,22,23,36].

Juan et al. [12] has reviewed biodiesel production from *jatropha curcas* oil by both catalytic and non-catalytic approaches. Some researchers have proposed the use of immobilized enzymes such as those from *chromo bacterium viscosum*, *candida rugosa*, and *susscrofa* porcine pancreas as catalyst [36]. The following section will give an overview of several previous studies conducted to produce biodiesel from *jatropha curcas*. More information can also be found in the following references [7,10,37–39].

Corro et al. [40] produced a high quality biodiesel from Mexican crude *jatropha curcas* oil by a two-step catalyzed process. In the first step, they investigated the activity of the solid catalyst SiO_2.HF for the esterification of free fatty acids in *jatropha curcas* oil with methanol. Solid acid catalyst was prepared by impregnating $SiO_2$with an appropriate amount of HF solution to obtain 10 wt % HF in the SiO_2. Then the suspension was stirred at room temperature for 1 h. After drying at 120 °C overnight, the catalyst called SiO_2–HF was calcined in air at 500 °C for 12 h. The catalyst showed a high number of Lewis acid surface sites but no CO_2 or H_2O adsorption activity. This, this catalyst showed high free fatty acid esterification activity with high stability. After 30 esterification runs, the catalyst activity remained unchanged. During the second step, the triglycerides present in the *jatropha curcas* oil were transesterified with methanol catalyzed by NaOH. The chromatographic analysis of the biodiesel obtained revealed that the process proposed in this investigation led to a very high quality of biodiesel, meeting the international requirements for its utilization as a fuel.

Zhu et al. [41] was performed optimization of *jatropha curcas* methyl ester using heterogeneous solid calcium oxide. The optimum condition for transesterification process was conducted at methanol/oil molar ratio of 9:1 with 1.5% of catalyst at reaction temperature of 70 °C for 2.5hours. The conversion of *jatropha curcas* methyl ester reaches 93% under the optimum conditions. It is show that calcium oxide is high activity solid catalyst in transesterification process. This production process is simple and repeatable and seems promising for potential application.

Qian et al. [42] studied the preparation of biodiesel from *jatropha curcas* oil produced by two-phase solvent extraction (TSE). The experimental results of TSE process showed that the optimal extraction conditions were 30 g samples from 240 mL of extraction solvent mixture and methanol/n-hexane volume ratio of 60:40 with extraction temperature 35 °C for extraction time 30 min. Furthermore, the effect of methanol recycling on the TSE process was also investigated. After TSE process, the investigations were carried out on transesterification of methanol with oil and n-hexane solution coming from TSE process in the presence of sodium hydroxide as the catalyst. The optimum conversion oil obtained was 98% of methyl ester by using 7:1 methanol/oil molar ratio, 60 °C reaction temperature and 120 min reaction time. The properties of fatty acid methyl ester product prepared from *jatropha curcas* oil produced by two-phase solvent extraction met the ASTM specifications for biodiesel.

Tiwari et al. [43] successfully produced biodiesel from *jatropha curcas* with high free fatty acids using a two-step catalyzed process. The optimum combination for reducing the free fatty acid of *jatropha curcas* oil from 14% to less than 1% was found to be 1.43% v/v H_2SO_4 acid catalyst, 0.28 v/v methanol to oil ratio and 88 min reaction time at a reaction temperature of 60 °C as compared to 0.16 v/v methanol-to-pretreated oil ratio, (3.5+acid value, w/w KOH) and 24 min of reaction time at a reaction temperature of 60 °C for producing biodiesel. This process gave an average yield of biodiesel for more than 99%. The fuel properties of *jatropha curcas* biodiesel obtained were found to be comparable to those of diesel and met the American and European standards.

Lu et al. [18] used a two-step process consisting of pre-esterification and transesterification to produce biodiesel from crude *jatropha curcas* oil. The free fatty acids in the oil were converted to methyl esters in the pre-esterification step using H_2SO_4 and solid acid catalyst SO_4^{2-}/TiO_2 prepared by calcining-metatitanic acid at 500 °C for 3 h as catalysts. The acid value of oil was reduced from the initial 14 mg KOH/g-oil to below 1.0 mg KOH/g oil in 2 h under the conditions of 12wt% methanol, 1wt% H_2SO_4 in oil at 70 °C. The conversion of free fatty acid was higher than 97% at 90 °C in 2 h using 4wt% solid acids and a molar ratio of methanol to free fatty acid of 20:1. Phospholipid compounds were eliminated during pre-esterification and a separate degumming operation was unnecessary. The yield of biodiesel by transesterification was higher than 98% in 20 min using 1.3wt% of KOH as catalyst and a molar ratio of methanol to oil 6:1 at 64 °C.

Berchmans and Harita [22] produced biodiesel from crude *jatropha curcas* seed oil having high free fatty acids (15% free fatty acid). In the first experiment biodiesel was produced using alkali base catalyzed transesterification process with an optimum NaOH to oil ratio and methanol to oil ratio of 3.3wt% and 70wt%. The presence of high concentration of free fatty acid deactivated NaOH catalyst and requires an addition of excess amount of NaOH. In this process, the yield of fatty acid methyl esters was only 55%. Therefore, two-stage transesterification process was selected to improve the methyl ester yield. In the first step, the high free fatty acid level of *jatropha curcas* oil was reduced to less than 1% by a two-step pretreatment process. This process was carried out using 60% w/w methanol-to-oil ratio in the presence of 1 wt% H_2SO_4 as an acid catalyst in 1 h reaction at 50 °C. After the reaction, the mixture was allowed to settle for 2 h and the methanol-water mixture was separated at the top layer. The second step was transesterification process using 24% w/w methanol to oil and 1.4% w/w NaOH to oil as alkaline catalyst to produce biodiesel at 65 °C. The final yield for methyl esters was achieved at 90% in 2 h.

Jain and Sharma [44] studied the kinetics of two-step acid-base catalyzed transesterification process for *jatropha curcas*. The process was carried out at pre-determined temperature of 65 °C for esterification and 50 °C for transesterification process. During this process, it was conducted on the optimum condition of methanol to oil ratio of 3:7 v/v, 1% w/w catalyst concentration for H_2SO_4 and NaOH and 400 rpm of stirring for 6 h. That process has been studied to convert triglyceride to methyl ester by ignoring the complex reactions by determining those six parameter reactions which is not only time consuming but costlier and needs much efforts. The constant rates for both the reactions are found as 0.0031 and 0.008 min^{-1}, indicating that the former is slower than the later reaction. The yield of methyl ester from esterification and transesterification are found as 21.2% and 90.1%, respectively. This also represents that the energy required for the transesterification to occur is also very small which is calculated as 87808.37 J/mol. The result offers opportunities for energizing remote areas through rural electrification since the low energy gives advantages for 'on farm' biodiesel production.

Deng et al. [45] studied the transesterification of high free fatty acid content *jatropha curcas* oil with methanol to biodiesel catalyzed directly by NaOH and high-concentrated H_2SO_4 or by two-step process in an ultrasonic reactor at 60 °C. The transesterification reactions with sodium hydroxide catalyst alone were performed at the following optimized conditions, methanol/oil ratio of 24% v/v (molar ratio 6:1), catalyst concentration of 1wt% (sodium hydroxide solid/*jatropha*-oil), stirring at 600 rpm and reaction time of 1 h. In this process, biodiesel yield was only 47.2% with saponification problem. When using concentrated sulfuric acid as catalyst the biodiesel yield increased to 92.8%,

the condition was 4 ml of sulfuric acid and 40 mL anhydrous methanol added to 100 ml *jatropha* oil at a stirring speed of 600 rpm. Besides, a two-step, acid-esterification and base-transesterification process was further used for biodiesel production. It was found that after the first-step pre-treatment with H_2SO_4 for 1 h, the acid value of *jatropha curcas* oil was reduced from 10.45 to 1.2 mg KOH/g, and subsequently NaOH was used for the second-step transesterification. Stable and clear yellowish biodiesel was obtained with 96.4% yield and 0.32 mg KOH/g after reaction for 30minutes. The total production time was only 1.5hours that is just half of the previous reported. The two-step process only needed 1.5 h to achieve 96.4% diesel yield. It could be concluded that the two-step process coupled with ultrasonic radiation is an efficient method for biodiesel production from crude oil with high free fatty acid value and it might be a practical application.

Deng et al. [46] synthesized hydrotalcite-derived particles with Mg/Al molar ratio of 3/1 by a precipitation method using urea as precipitating agent, subsequently with (MHT) microwave-hydrothermal treatment, and followed by calcination at 773 K for 6 h. These particles were used as catalysts for biodiesel production from *jatropha curcas* oil. Experiments showed that the direct transesterification of *jatropha curcas* oil to biodiesel catalyzed by solid catalyst had a low conversion rate. Even using longer reaction time, only 80.4% biodiesel yield was achieved. Therefore, a two-step process of *jatropha curcas* oil to biodiesel was used to resolve the problem. First, an acid-esterification pre-treatment was performed with concentrated sulfuric acid as catalyst. In this reaction, 2% v/v of sulfuric acid, 20% v/v of anhydrous methanol were added to *jatropha curcas* oil and vigorously stirred and refluxed at 318 K in an ultrasonic reactor for 1.5 h. In the second step, a base-catalyzed transesterification reaction was carried out in the same ultrasonic reactor with the calcined hydrotalcite catalyst. In this reaction, 210 W ultrasonic powers, (4:1) methanol to oil ratio, 1.0 wt% catalyst at 318 K for 1.5hours was used. The yield of biodiesel obtained was 95.2%. The biodiesel properties were close to those of the German standard (DIN V51606). It has been found that after removing the glycerol on the surface, the catalyst can be reused for 8 times. The authors concluded that the calcined hydro talcitenano catalyst combined with ultrasonic radiation is an effective method for the production of biodiesel from *jatropha curcas* oil.

Kywe and Oo [47] produced biodiesel from *jatropha curcas* using methanol and ethanol and sodium and potassium hydroxide. From the lab scale, it was found that the maximum biodiesel yield 76% was obtained from free fatty acid 22.6% in raw *jatropha curcas* oil. This method is carried out by using sodium hydroxide catalyst concentration 1%, reaction temperature 65 °C with reaction time one hour and molar ratio of methanol to oil 6:1. The maximum biodiesel yield of 73% from free fatty acid 8.8% in raw *jatropha curcas* oil was obtained at optimal potassium hydroxide catalyst concentration 1%, reaction temperature-room temperature, reaction time 5hours and molar ratio of ethanol to oil 8:1.

Hawash et al. [48] studied the transesterification of *jatropha curcas* oil using CaO as a solid base catalyst. Experimental results revealed that a 12:1 M ratio of methanol to oil in addition of 1.5% (w/v) CaO catalyst and 70 °C reaction temperature has produced an optimum biodiesel yield of more than 95% after 3 h reaction time. Moreover, the authors studied transesterification of *jatropha curcas* oil using super base calcium oxide as catalyst under super-critical conditions (200 °C & 24 bars) and molar ratio 12:1. They found out that this reaction required only one hour achieving 96% of oil conversion. The authors also studied transesterification of *jatropha curcas* oil with methanol using sulfated zirconium at 120 °C for 1 h using molar ratio 12:1 methanol: oil with two different doses of the catalyst 2% w/v and 5% w/v. The results revealed that only 10% and 30% conversion were obtained.

Nakpong and Wootthikanokkhan [49] produced biodiesel from crude *jatropha curcas* oil by alkali-catalyzed methanolysis.. The optimum conditions were a methanol to oil molar ratio of 6:1, NaOH concentration of 1.0 wt% of oil, a reaction temperature of 60 °C, and a reaction time of 40minutes. The methyl ester content under these optimum conditions was 98.6 wt%.

Foidl et al. [50] prepared methyl and ethyl esters from *jatropha curcas* seeds oil. Methyl ester was prepared by reacting 2000 g of crude oil (2.3 mol) with a solution of 30 g KOH (0.53 mol) in 331 g methanol (10.34 mol) and the reaction was carried out in two step process at 30 °C. First, the oil was mixed with methanolic KOH solution and the reaction mixture was stirred for 30 min before transferred to a separation funnel. After 5 h, the glycerol layer was separated. The organic layer was mixed with one part of the methanolic KOH solution and stirred further for 30 min. After another 5 h, the glycerol layer was separated and the esters were washed three times with 500 ml of warm water each (50 °C) to remove traces of soap and glycerol and dried over Na_2SO_4 to obtain 1850 g of pure methyl esters (92% of theoretical yield). Ethyl ester was prepared by reacting 1000 g crude oil (1.14 mol) with a solution of 30 g KOH (0.53 mol) in 317.7 g ethanol (6.9 mol). The reaction mixture was stirred at 75 °C for 90 min before it was transferred to a separation funnel. The upper layer (671 g), mainly consist of ethyl esters, and the lower layer (907 g) contained glycerol, ethyl esters and potassium salts. Esterification of the free fatty acids was done by mixing the organic layer (290 g) with 5.8 g H_2S0_4 and 69.0 g ethanol. Then the reaction mixture was stirred at 80 °C for 6 h in this process and the yield of ethyl esters was reported to be 88.4%.

3. Biodiesel production

3.1. Jatropha curcas seed oil and reagents

The matured *jatropha curcas* seeds were collected from Cilacap and Kebumen, West Java province, Indonesia. Crude *jatropha curcas* oil was obtained by mechanically expelling the seeds. The crude oil was filtrated to remove solid impurities. Methanol (99.9% purity), toluene (99.9% purity), HCL (purity 37%), H_2SO_4 (purity $>98.9\%$), H_3PO_4 (10% concentration), NaOH, (purity 99.9%), KOH (purity 99%), CH_3ONa (purity 99%), CH_3OK (purity 99%), $CaCl_2$ (anhydrous 99%), Na_2SO_4 (anhydrous 99%) and qualitative filter paper (filter fioroni, France) were obtained from Metta Karuna Enterprise (Kuala Lumpur, Malaysia)

3.2. Crude jatropha curcas oil (CJCO) properties

Crude *jatropha curcas* oil from different sources has slightly different properties and fatty acid compositions varying by location. The physicochemical properties of crude *jatropha curcas* oil such as viscosity at 40 °C, density at 15 °C, flash point, calorific value, acid value and iodine value were analyzed and compared to other crude *jatropha curcas* oil in the literature given in Table 1 [11,14,20,29,44–47,49,51–63]. It can be seen from Table 1 the viscosity of crude *jatropha curcas* is within the range of 8.72 mm^2/s–52.76 mm^2/s and the density in the range of 892.0 kg/m^3–940.0 kg/m^3. Besides, the calorific values are in the range of 38.20 MJ/kg–42.15 MJ/kg. In this study, high viscosity of 28.35 mm^2/s and high acid of 12.73 mg KOH/g of CJCO suggests that the conversion oil using pretreatment process followed by two-step esterification and transesterification process. Several researchers have been investigated that crude *jatropha curcas* oil contains high viscosity and high free fatty acid. Berchmans and Hirata [22] have identified *jatropha crucas* oil has high free fatty acid of 14.9% w/w. However, Lu et al. [18] stated that *jatropha*

curcas oil with high content of free fatty acids cannot directly convert via an alkali catalyzed transesterification process because free fatty acid will react with alkali catalyst to form soaps. This will cause the emulsification and separation problems. Furthermore, Yee et al. [64] extracted *jatropha curcas* seed and revealed that it contains high acid value of 22.7 m_{KOH}/m_{Oil}.

The fatty acid composition for the crude *jatropha curcas* oil was detected using gas chromatography. GC model Agilent 7890 was used to analyze the fatty acid composition with flame ionization detector and helium as a carried gas. The column was packed with ZB-wax column (30 m × 0.25 mm × 0.25 μm). Injection port was maintained at 250 °C. The starting temperature of oven was maintained at 100 °C and increased by 10 °C per min to final oven temperature of 250 °C. The fatty acid composition of crude *jatropha curcas* oils were determined as lauric (C12:0), myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1) linoleic (C18:2), linolenic (C18:3) and arachidic (C20:0). The percentage of fatty acid composition for the present study was generally agreed with previously reported studies which are summarized in Table 2. Oleic acid is the main acid with value of

Table 1
The comparison of properties of **c**rude *jatropha curcas* oil.

Kinematic viscosity (mm^2/s)	Density (kg/m^3)	Flash point (°C)	Calorific value (MJ/kg)	Acid value (mg KOH/g)	Iodine value (g I_2/100 g)	Ref.
28.35	915.0	190.5	38.96	12.70	80.8	Result
34.84	918.6	–	–	–	–	[8]
35.4	–	459	–	–	101	[11]
49.93	918.6	240	39.774	–	–	[105]
51	932	242	37.01	–	–	[44]
40.06	916	235	39.63	3.71	101.7	[84]
17.1	–	–	–	3.5	105.2	[52,53]
36.9	917.7	99	42.048	–	–	[56]
41.51	–	–	–	–	100.1	[47]
24.5	892	498	38.65	10.5	–	[46]
52.76	932.92	210	38.2	–	94	[63]
–	–	–	–	4.11	59.6	[61]
37–54.8	–	210–240	37.83–42.05	0.92–6.16	92–112	[14]
52.76	–	110	39.77	–	–	[58]
49.9	918	240	39.77	–	–	[54]
24.5	940	225	38.65	28	–	[29]
35.98	917	229	39.071	–	–	[39,60]
55	–	–	39.5	–	–	[59]
40.4	917	274	39.86	38.2	112.5	[55]
29.4	920	225	–	28	–	[57]
34.84	918.7	–	–	–	–	[49]
8.72	912	125	–	–	10.47	[47]
24.50–52.76	901–940	180–280	38.20–42.15	–	–	[20]

Table 2
Fatty acid composition of crude *jatropha curcas* oil.

Fatty acid composition (%)												Ref.
C12:0 Lauric	C14:0 Myristic	C16:0 Palmitic	C16:1 Palmitoleic	C18:0 Stearic	C18:1 Oleic	C18:2 Linoleic	C18:3 Linolenic	C20:0 Arachidic	C22:0 Behenic	C22:1 Erucic	C24:0 Lignoceric	
0.1	0.1	13.0	0.7	5.8	44.5	35.4	0.3	0.2	–	–	–	Result
–	–	12–17	–	0–5	35-64	19-42	2–4	–	–	–	–	[70]
–	1.4	15.6	–	9.7	40.8	32.1	–	0.4	–	–	–	[30,67]
–	–	13.4–15.3	–	6.4–6.6	36.5– 41.68	42.1–35.5	0.3	–	–	–	–	[8,36]
–	0–0.1	14.1–15.3	0–1.3	3.7–9.8	34.3–45.8	29.0–44.2	0–0.3	0–0.3	0–0.2	–	–	[12,22,44,66,105]
–	–	19.5 ± 0.8	–	6.8 ± 0.6	41.3 ± 1	31.4 ± 1.2	–	–	–	–	–	[52]
–	–	18.22	–	5.14	28.46	48.18	–	–	–	–	–	[73]
–	–	11.3	–	17	12.8	47.3	–	4.7	0.6	–	4.4	[53]
–	0.1	13.6	0.8	7.4	34.3	43.2	0.2	0.3	–	–	–	[50]
–	0.38	16	1–3.5	6–8	42–43.5	33–34.5	0.8	–	–	–	–	[74]
–	–	7.3	–	–	51.4	29.2	2.6	–	–	–	–	71
–	–	15.2	0.7	6.8	44.6	32.2	0.2	0.2	–	–	–	[61]
–	–	14.2	1.4	6.9	43.1	34.4	–	–	–	–	–	[14]
–	0.1	14.2–15.1	0.7–0.9	7.1	44.7	31.4–32.8	0.2	0.2	0.2	–	–	[15,32,58]
0.31	–	13.38	0.88	5.44	45.79	32.27	–	–	–	–	–	[54]
–	–	12.6	–	3.9	41.8	–	7.8	–	–	–	–	[55]
–	–	13.77	–	6.77	41.68	35.55	–	–	–	–	–	[49]
0.14	0.17	14.82	0.81	4.15	40.98	38.61	0.27	0.06	–	–	–	[75]
–		13.23	0.85	5.4	41.62	36.99	0.22	–	–	–	–	[72]
–	0.91	3.45	2.72	8.79	42.28	37.62	0.56	–	–	–	–	[68]
–	–	16.8	7.7	7.7	36	0.2	–	–	–	–	–	[76]
–	–	13.9	–	7.8	55.9	19.6	1.4	1.2	–	0.2	–	[21]
–	1.4	11.3	–	17.0	12.8	47.3	–	4.7	–	–	–	[69]
–	0.5–1.4	12.0–17.0	–	5.0–9.5	37–63	–	19–41	0.3	–	–	–	[27]
–	16.0	6.5	–		43.5	34.4	0.80	–	–	–	–	[65]
–	–	14.4	0.1	3.6	43.2	38.7	–	–	–	–	–	[64]

44.5%, followed by linoleic (35.4%), palmitic (13.0%) and stearic (5.8%). Since crude *jatropha curcas* oils consist of unsaturated fatty acids (oleic and linoleic acids) it shows that *jatropha curcas* biodiesel has good low temperature properties [14].

3.3. Determination of acid value and the free fatty acid

Acid value and the free fatty acid percentage of crude oil and degummed oil were measured following AOCS Cd 3a-63 method [77]. Free fatty acid percentage is the number of gram for fatty acid in 100 ml of oil. Moreover, acid value is the number of milligrams of potassium hydroxide needed to neutralize the free fatty acid in 1 g of oil sample. KOH solution with normality 0.10 was used as titrated solution to measure acid value and free fatty acid. The first step is to measure oil sample about 1.0 ± 0.05 g before putting into a conical flask. Then, 50 mL of toluene was added together with a few drops of phenolphthalein indicator. This mixture was titrated by KOH solutions and stirred vigorously until the mixture changed into pink color permanently. The acid value was expressed as mg KOH/g of oil by Eq. (1) and % free fatty acid as following Eqs. (2)–(4) [77]. Table 3 shows the details calculation of free fatty acid value for crude jatropha curcas oil, degummed jatropha curcas and esterified jatropha curcas.

$$\text{Acid value} = \left(\frac{V \times N \times MW_{\text{KOH}}}{W}\right) \ \text{(Expressed in mg KOH/g)} \quad (1)$$

$$\%FFA = \left(\frac{V \times N \times MW_{\text{C18:1}}}{W \times 1000}\right) \ \text{(Expressed as oleic acid)} \quad (2)$$

$$\%FFA = \left(\frac{V \times N \times MW_{\text{C18:2}}}{W \times 1000}\right) \times 100\% \ \text{(Expressed as linoleic acid)} \quad (3)$$

$$\%FFA = \left(\frac{V \times N \times MW_{\text{C16:0}}}{W \times 1000}\right) \times 100\% \ \text{(Expressed as palmitic acid)} \quad (4)$$

where

V = potassium hydroxide solution consumed in the titration (mL)
N = normality of the potassium hydroxide solution
W = weight of oil sample (g)
MW = molecular weight (g/mol)
MW_{KOH} = 56.1 g/mol
$MW_{\text{C18:1}}$ = 282.5 g/mol
$MW_{\text{C18:2}}$ = 280.4 g/mol
$MW_{\text{C16:0}}$ = 256.4 g/mol

3.4. Pretreatment of crude jatropha curcas oil

The crude *jatropha curcas* oil was prepared by degumming process with H_3PO_4 (10%) to remove FFA(<0.2 mg KOH/g) oil, water(<0.1%), phospholipids(<0.04%) and other impurities. This pretreatment was done to refine *jatropha curcas* oil in order to improve the quality of the oil before esterification process. Koh and Ghazi [14] reviewed that *jatropha curcas* oil has high free fatty acid contents. Thus, need modified and developed methods such as steam distillation, extraction by alcohol and esterification by acid catalyst (acid neutralization) to reduce free fatty acid in the oil. These methods were also discussed in the studies carried out by Leung et al. [57], Atabani et al. [9], Karmakar et al. [27] and Marchetti [78].

3.5. Esterification and transesterification process

In general, esterification and transesterification (two-steps) process have been proposed for reducing the high free fatty acid content of the oils. There are many methods used in this process such as homogenous catalyst, heterogeneous catalyst and supercritical methanol transesterification. In this study, the crude *jatropha curcas* oil has free fatty acid above 2% and it is suggested to use two acid–alkaline transesterification processes. Lu et al. [18] and Koh and Ghazi [14] also investigated the approach with acid catalyst (H_2SO_4) to reduce acid value and remove small amount water in refine oil. However, Leung et al. [57] reported that solid catalyst has better benefit than homogeneous acid catalyst. It can help to eliminate separation, corrosion, toxicity and environmental problems but the reaction is slower. They also stated that one-step esterification may not reduce free fatty acid due to high content of water produced during the reaction. This required about 2 h for this process and water must be removed by separation funnel before adding the mixture into oils for esterification.

3.5.1. Acid-catalyst esterification

Acid catalyst esterification was used to reduce free fatty acids content to a safer level for alkaline transesterification. Generally, sulfuric, hydrocholric, ferric sulfate, phosphoric and organic sulfonic acid have been used to reduce acid value for high free fatty acids and water of vegetable oils [1]. However, some researchers have claimed that acid esterification process was characterized by slow reaction ratio of methanol and triglycerides. Karmakar et al. [27] reported that esterification process required 20:1 methanol ratio to oil. This reaction indicated that higher molar ratio preferred to reduce acid value into desired limit before alkaline transesterification process. Moreover, this process was conducted by many researcher such as Gerpen et al. [79], Ramadhas et al. [80] and Sahoo and Das [65]. They successfully decreased the free fatty acid value of the feedstock below 1% after using esterification process.

In this process acid catalyst HCl and H_2SO_4 are used for esterification with 9:1 M ratio of methanol to refine *jatropha curcas* and 1%v/v of acid catalyst were added to the pre-heated oils at 60 °C for 3hour under 1000 rpm stirring speed in a glass reactor. Upon the completion of this reaction, the products were poured into a separating funnel to separate the excess alcohol, acid catalyst and impurities presented in the upper layer. The lower layer was separated and entered into a rotary evaporator and heated at 65 °C under vacuum conditions for 1 h to remove methanol and water from the esterified oil.

Table 3
The detailed procedures conducted to calculate the percentage free fatty acid value of crude *jatropha curcas* oil, degummed *jatropha curcas* and esterified *jatropha curcas*.

Name sample	Weight sample (g)	Normality KOH	Volume KOH (mL)	Acid value (mgKOH/gr)	% of free fatty acid (Oleic acid)	% of free fatty acid (Linoleic acid)	% of free fatty acid (Palmitic acid)
CJCO	1.05	0.10	2.34	12.70	0.45	0.45	0.50
Degummed CJCO	1.05	0.10	1.97	10.71	0.38	0.38	0.42
Esterified HCl	1.05	0.10	0.31	1.69	0.06	0.06	0.07
Esterified H_2SO_4	1.05	0.10	0.32	1.74	0.06	0.06	0.07

3.5.2. Alkaline-catalyzed transesterification

Transesterification or alcoholysis is defined as the chemical reaction of alcohol with vegetable oils. In this reaction, methanol and ethanol as well as KOH and NaOH catalyst are the most commonly used alcohols because of their low cost and availability [9]. However, in the study by Demirbas [7] and Singh et al. [34] stated that metal alkoxides catalyst will give higher yields (> 98%) in short times (30 min). In this study, the transesterification were carried out using homogenous method and four catalysts (NaOH, KOH, CH_3ONa, and CH_3OK) were used in this reaction.

In this process, esterified *jatropha curcas* oil was reacted with 9:1 of methanol to oil ratio and 1% w/w of alkaline catalyst was maintained at 50 °C for 2 h and stirring speed of 1000 rpm. After the reaction is completed, the produced biodiesel was deposited in a separation funnel for 4 h to separate glycerol from biodiesel. The lower layer which contained impurities and glycerol was drawn off. The JCME formed in the upper layer was entered into a rotary evaporator to remove the remaining methanol. The process was followed by washing with distilled water to remove the entrained impurities and glycerol. In this process, 50% v/v of distilled water at 50 °C was sprayed over the surface of the esters and stirred gently. This process was repeated several times until the pH of the distilled water became neutral. The lower layer was discarded and upper layer was entered into a flask. The methyl ester was dried using $CaCl_2$ anhydrous for 1 day follow by Na_2SO_4 for 3 h and filtered by a paper filter. Finally, the methyl ester was further purified using rotary evaporator at 65 °C for 1 h to remove the water from biodiesel. Fig. 3 shows the process flowchart of *jatropha curcas* biodiesel production methods [12,27].

3.6. Characterization of jatropha curcas methyl ester

The physical and chemical properties of the *jatropha curcas* methyl ester produced in this study were tested using ASTM D6751 or EN 14214 standards. Table 4 shows a summary of the equipment used and methods complied to analyze the physical and chemical properties. Moreover, Table 5 shows the data and procedures according to the norms and limits established by ASTM D6751 and EN 14214 standard [1,4,8,9,16,20,81–83].

4. Properties *jatropha curcas methyl* ester

The physical and chemical properties of *jatropha curcas* methyl ester, petrol diesel compared with other *jatropha curcas* methyl ester, *azadirachta indica* methyl ester, *pongamia pinnata* methyl ester and *ricinus communis* methyl ester carried out by researchers are listed in Table 6. A comparison between the results obtained and the results from the literature are included in these tables. It can be seen that most of the properties have met ASTM D6571 and EN 14214 standards. The important aspect of biodiesel and corresponding effects are highlighted in the following sections.

4.1. Kinematic viscosity

Kinematic viscosity is defined as the resistance of liquid to flow and is the most important fuel features. It affects the operation of

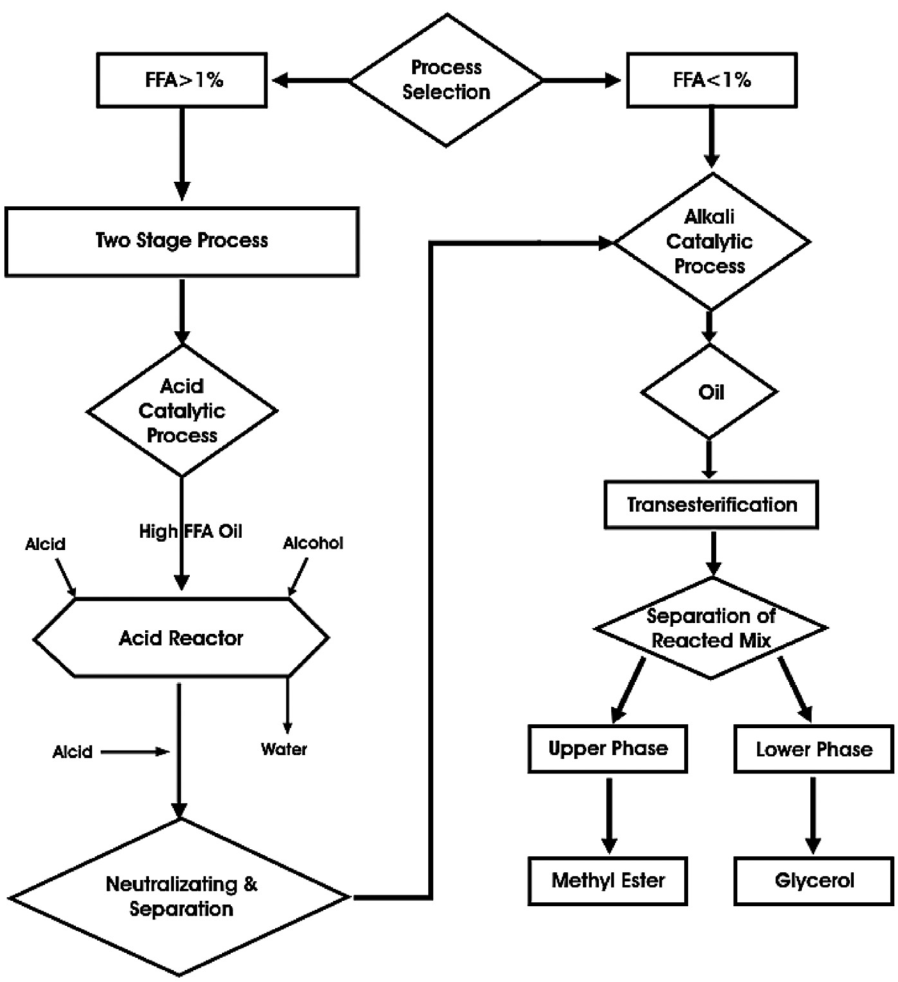


Fig. 3. Process selection and steps for *jatropha curcas* biodiesel production [13,27].

Table 4
List of equipment used for properties test.

Property	Equipment	Standard method	Accuracy
Kinematic viscosity	NVB classic (Normalab, France)	ASTM D445	± 0.01 mm^2/s
Density	DM40 LiquiPhysics™ density meter (Mettler Toledo, Switzerland)	ASTM D127	± 0.1 kg/m^3
Flash point	NPM 440 Pensky-martens flash point tester (Normalab, France)	ASTM D93	± 0.1 °C
Cloud and pour point	NTE 450 Cloud and pour point tester (Normalab, France)	ASTM D2500	± 0.1 °C
Calorific value	6100EF Semi auto bomb calorimeter (Perr, USA)	ASTM D240	± 0.001 MJ/kg
Acid value and iodine value	Automation titration rondo 20 (Mettler Toledo, Switzerland)	ASTMD664 and EN 14111	Acid number ± 0.001 mg KOH/g, iodine value ± 0.1 I_2 mg/g and deviation 0.001%
Carbon canradsons residue (100 sample)	NMC 440 micro-carbone conradson residue tester (Normalab, France)	ASTM D4530	± 0.01%
Copper strip corrosion (3 h at 50 °C)	Seta copper corrosion bath 11300-0 (Stanhope-Seta, UK)	ASTM D130	–
Sulfate ash content	Professional laboratory furnace Model L40/11 (Nabertherm, Germany)	ASTM D874	± 0.001%
Sulfur content (S 15 grade and S500 grade)	Multi EA 5000 (Analytical jena, Germany)	ASTM D6667	± 0.01 ppm
Oxidation stability,110 °C	873 Rancimat (Metrohm, Switzerland)	EN 14112	± 0.01 h
Methanol content	Agilent 7890 gas chromatograph (Agilent, USA)	EN 14110	± 0.008% or 0.0008 min
FAME content		EN 14103	
Cetane number	92000-3 Ignition quality tester (IQT™) (Stanhope-Seta, UK)	ASTM D6890	± 0.1
Water content	837 KF coulometer (Metrohm, Switzerland)	EN ISO 12937	± 0.001%

Table 5
ASTM D6751 and EN 14214 standard test limit for biodiesel properties [1,4,8,9,16,20,81–83].

Fuel properties	Unit	Biodiesel			
		Test limit		Test method	
		ASTM D6751	EN 14214	ASTM	EN
Density 15 °C	(kg/m^3)	880	860–900	D1298	EN ISO 3675/12185
Viscosity at 40 °C	(mm^2/s)	1.9–6.0	3.5–5.0	D445	EN ISO 3104
Cetane number	–	Min 47	Min 51	D613	EN ISO 5165
Iodine value	I_2/100 g	–	Max 120	–	EN 14111
Calorific value	MJ/kg	–	35	–	EN 14214
Acid value	mg KOH/g	Max. 0.50	Max 0.5	D664	EN 14104
Pour point	°C	−15 to16	–	D97	–
Flash point	°C	Min 130	Min 120	D93	ISO DIS 3679/2719
Cloud point	°C	−3 to 12	–	D2500	–
Methanol content	% m/m	Max 0.20	Max 0.20	EN 14110	EN 14110
Water content	% v/v	Max. 0.05	Max. 500μg/g	D2709	EN ISO 12937
Sulphated ash	% m/m	Max. 0.02	Max. 0.02	D874	EN ISO 3987
Conradson carbon residue	m/m	Max. 0.05	Max. 0.03	D4530	EN ISO 10370
Oxidation stability at 110 °C	hours	Min. 3	Min. 6	D675	pr EN 15751/EN 14112
FAME content	% m/m	–	Min 96.5	–	EN 14103

fuel injection, blending formation and combustion process [7,9,16,89,90]. The high viscosity interferes with the injection process and leads to insufficient fuel atomization [89,90]. Structural features fatty acid composition such as chain length, degree of unsaturation, double bond orientation, and type of ester head group can influence the kinematic viscosities of biodiesel [7,9,16,89]. Viscosity increases with the increase in the chain length and decreases with the increase in the number of double bonds (unsaturation chain level) [90,91]. According to ASTM D6751 and EN 14214 standards, viscosity must lie between 1.9–6.0 mm^2/s and 3.5–5.0 mm^2/s [1,4,8,9,16,20,81–83]. As seen in Table 6 that the viscosity of JCME (HCl–NaOH, HCl–KOH) and JCME (H_2SO_4–NaOH, H_2SO_4–KOH, H_2SO_4–CH_3ONa and H_2SO_4–CH_3OK) obtained in this study are given in the range of 4.62 mm^2/s–4.84 mm^2/s. These results were also compared with other JCME as shown in Fig. 4. The viscosity of JCME is within the range of 4.20 mm^2/s–5.65 mm^2/s except the findings from Forson et al. [56] It can be conclude that all JCME results are comply with the standard specified by ASTM D6751 of (1.9 mm^2/s–6 mm^2/s). However, if compared with PPME, RCME and AIME, it is found that RCME possess the highest viscosity of 10.50 mm^2/s [82,86] followed by AIME (5.21 mm^2/s) [36,82,87] and PPME (4.85 mm^2/s) [36,92,93].

4.2. Density

Density is another important property of biodiesel. It also influences the efficiency of the fuel atomization for airless combustion systems [94–96]. The density of fuel has some effect on the break-up of the fuel injected into the cylinder. In addition, more fuel is injected by mass as the fuel density increases. All biodiesel fuels regardless of produced from vegetable oils or from fats are denser and less compressible than the diesel fuel [90]. According to ASTM D6751 and EN 14214 standards, density should be 860 kg/m^3–900 kg/m^3 for biodiesel standard (Table 5) [1,4,8,9,16,20,81–83]. Table 6 shows that the density for JCME (HCl–NaOH, HCl–KOH)

and JCME (H_2SO_4–NaOH, H_2SO_4–KOH, H_2SO_4–CH_3ONa and H_2SO_4–CH_3OK) are in the range of 861.8 kg/m^3–876.6 kg/m^3. These results were also compared with other JCME shown in Fig. 5. It can be seen that the density of all *jatropha curcas* biodiesel were in line within the range specified in biodiesel standards. However, the density of PPME (890 kg/m^3) and RCME (913.0 kg/m^3) are higher than all *jatropa curcas* biodiesel [36,92,93].

4.3. Flash point

The flash point is the temperature at which the fuel will start to burn when it comes to contact with fire. It is an important parameter from the safety point of view such as safe for transport, handling, storage purpose and safety of any fuels [18,33,49,66,94,97–99]. According to ASTM D6751 and EN 14214 standards, biodiesel have a flash point not lower than 120 °C. This is higher than petrol diesel which has a flash point of 71 °C. The higher flash point of the former is probably because JCME has less volatile impurities which are an important fuel feature for an engine's starting and warming. However, a fuel with high flash point may cause carbon deposits in the combustion chamber [9,16,20,90,91]. From Table 6, it can be seen that the flash point of JCME (HCl–NaOH, HCl–KOH) and JCME (H_2SO_4–NaOH, H_2SO_4–KOH, H_2SO_4–CH_3ONa and H_2SO_4–CH_3OK) obtained in this study was in the range of 172.5 °C–184.5 °C. These results were also compared with other JCME, PPME, RCME and AIME as shown in

Table 6
Comparison on physical and chemical properties of *jatropha curcas* methyl ester.

Fuel	Kinematic viscosity (mm^2/s)	Density (kg/m^3)	Flash point (°C)	Cloud point (°C)	Pour point (°C)	Calorific value (MJ/kg)	Acid value (mg KOH/g)	Iodine number (g I_2/100 g)	Condradson carbon residue (%mass)	Sulphated ash (%mass)	Water content (mg/kg)	Methanol (%mass)	Refs.
Petrol diesel	2.91	839.0	71.5	1.0	2.0	45.82	0.17	–	0.875	0.02	38.7	–	Result
JCME (HCl–NaOH)	4.84	862.9	176.5	6.0	−5.0	39.58	0.29	109.5	0.056	0.004	306.0	0.04	
JCME (HCl–KOH)	4.62	876.6	174.5	6.0	−5.0	39.19	0.32	109.4	0.055	0.005	315.0	0.04	
JCME (H_2SO_4–NaOH)	4.36	861.8	172.5	6.0	−3.0	39.78	0.33	101.6	0.055	0.006	352.0	0.04	
JCME (H_2SO_4–KOH)	4.76	862.7	170.5	6.0	−1.5	39.70	0.28	105.5	0.055	0.008	316.0	0.04	
JCME (H_2SO_4–CH_3ONa)	4.79	862.6	184.5	3.0	−3.0	39.62	0.29	102.7	0.059	0.007	457.0	0.04	
JCME (H_2SO_4–CH_3OK)	4.77	863.4	174.5	3.0	−3.0	39.70	0.30	102.6	0.059	0.005	445.0	0.04	
JCME	4.84	879.0	191	–	–	–	0.24	–	0.025	–	0.16 (% v/v)	0.06	[70]
JCME	4.84–5.65	864.0–880.0	170–192	–	–	38.45–41.00	0.5	93–106	0.02–0.50	0.005–0.010	0.07–0.10 (% v/v)	0.06–0.09	[24]
JCME	4.40	–	163	4	–	–	0.48	–	< 0.01	0.002	0.05 (% v/v)	–	[5]
JCME	4.80	880.0	135	–	2	39.23	0.40	–	0.200	0.012	0.025 (% v/v)	–	[43]
JCME	4.32	880.3	> 130.0	–	–	–	0.27	–	0.060	–	480	–	[8]
JCME	4.25	–	> 160.0	2.7	–	–	–	–	0.026	–	< 0.005 (% v/v)	–	[82]
JCME	5.38	–	93	–	−1	–	–	101	–	–	–	–	[11]
JCME	4.2	875.0	186	–	–	39.65	0.27	95–106	0.180	–	–	–	[84]
JCME	4.80	880.0	188	10.0	6.0	–	0.40	–	–	0.016	–	–	[88]
JCME	5.7	866.9	86	–	15	45.9	–	–	–	–	–	–	[56]
JCME	3.6	–	153	1	–	–	0.48	–	0.000	0	0.01 (% v/v)	–	[42]
JCME	3.96	882.0	133	–	6	–	0.32	–	–	–	0.047 (% v/v)	–	[47]
JCME	3.00–5.65	862–886	180–280	2–6	4–10	37.2–43.0	–	–	–	–	–	–	[21]
JCME	6.7	–	126	–	–	38.58	–	–	–	–		–	[58]
JCME	4.40	884.2	172	–	–	–	0.11	93	–	< 0.01	590	< 0.02	[85]
JCME	5.65	880.0	170	–	–	38.45	–	–	–	–	–	–	[54]
JCME	–	880.0	135	–	2	39.23	0.4	–	0.200	0.012	0.025 (% v/v)	–	[29]
JCME	5.34	620	–	–	–	41.00	–	–	–	–	–	–	[59]
JCME	3.57	880	174	–	–	39.34	0.38	–	0.024	–	–	–	[55]
JCME	4.31	880.2	147	–	−8	–	0.04	–	–	0.01	–	–	[72]
PPME	4.85	890	180	–	–	–	0.42	89	0.002	–	0.005 (% v/v)	0.005	[36,92,93]
RCME	10.50	913.0	149	–	−13.4	39.16	1.008	–	–	0.034	< 0.005 (% v/v)	–	[86]
AIME	5.213	–	–	–	14.4	35.2	0.649	–	0.105	< 0.005	–	–	[35,87]

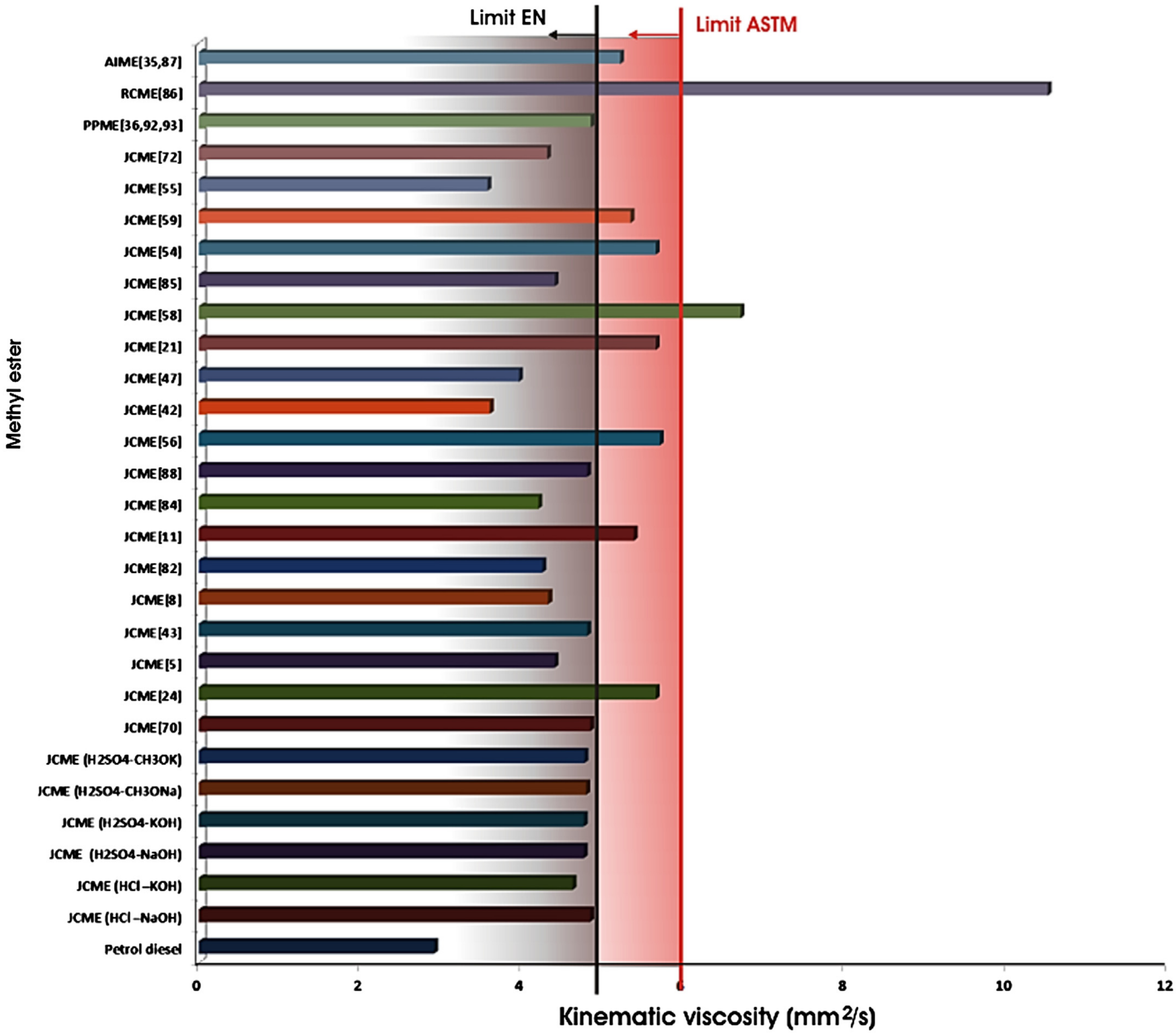


Fig. 4. Kinematic viscosity of JCME from different homogenous catalysts compared with other JCME, PPME, RCME and AIME.

Fig. 6. It has been observed that all of the produced biodiesel agree with the specification of flash point in ASTM D6751. However, according to Mahanta and Shrivastava [58] the lowest flash point was at 126 °C for JCME while No [20] reviewed that the flash point was 280 °C.

4.4. Pour point and cloud point

The important parameters for low temperature applications of a fuel are cloud point and pour point. The cloud point is the temperature at which wax first becomes visible when the fuel is cooled [16,20]. The pour point is the temperature at which the amount of wax, out of the solution, is sufficient to gel the fuel [62,94,100]. The standards pour point for biodiesel is −15 °C to 16 °C and cloud point is −3 °C to 12 °C as shown in Table 5 [1, 4, 8, 9, 16, 20, 81–83]. Structural features such as chain length, degree of unsaturation, orientation of double bonds and type of ester head group strongly influence the individual chemical constituents of biodiesel. As can be seen from Table 2, *jatropha curcas* oil has dominant unsaturated chain and it will increase low temperature compared to saturate chain such as palm oil and soybean oil. Moreover, the orientation of the double bond is another important factor influencing the low temperature. Most of all naturally occurring unsaturated fatty acids contain double bond [1,9,16,69,89,90]. However, it can be seen from Table 6 that the cloud point and pour point for JCME are in the range of 3.0 °C −6.0 °C and −5.0 °C–1.5 °C. These results were also compared with other JCME and three of non-edible biodiesel (PPME, RCME and AIME) as shown in Fig. 7. It has been observed that most of the cloud point and pour point of JCME satisfies the biodiesel standards. The highest pour point of JCME was obtained by Forson et al. [56] at 15 °C followed by AIME at 14.4 °C [36,82,87]. Moreover, Rashid et al. [88] and No [20] stated that the highest is RCME at −13.4 °C while the lowest is from JCME at 10 °C.

4.5. Calorific value

Calorific value is a measure of the energy produced when the fuel is burnt completely which also determines the suitability of biodiesel as an alternative to diesel fuel. However, the calorific value of biodiesel

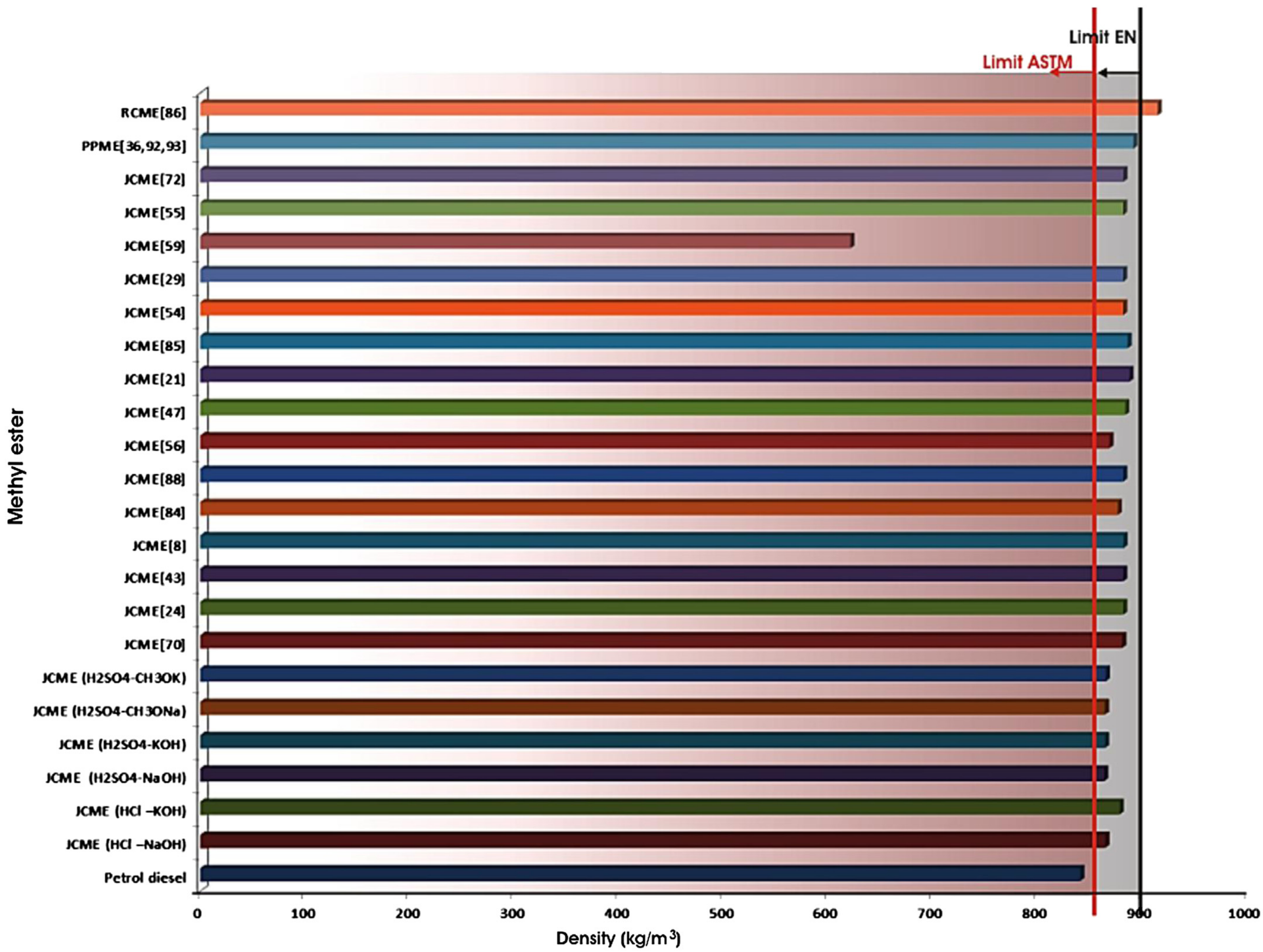


Fig. 5. Density of JCME from different homogenous catalysts compared with other JCME, PPME and RCME.

is normally lower than diesel due to the oxygen content of biodiesel [96]. The higher oxygen content in biodiesel could improve the combustion process and decrease its oxidation potential [7]. The standard calorific value of biodiesel is 35 MJ/kg (EN 14214) compared to 45.82 MJ/kg for petrol diesel. Table 6 listed the results of JCME were in the range of 39.19 MJ/kg–39.78 MJ/kg as shown in Fig. 8. These results were also compared with JCME, PPME, RCME and AIME. Forson et al. [56] suggested the highest calorific value was 45.9 MJ/kg which is higher than petrol diesel [36,82,87]. It can be seen that all of these results are comply with the standards specified by EN 14214. Similary, Demirbas [7] reported that calorific value of biodiesel is relatively high (39 MJ/kg–41 MJ/kg) but slightly lower than gasoline (46 MJ/kg) and petrol diesel (43 MJ/kg) [7,37].

4.6. Acid value

The acid value or neutralization number is expressed as the amount of KOH in mg required to neutralize 1 g of fatty acid methyl esters. It reflects the presence of free fatty acids or acids used in the manufacture of biodiesel and also the degradation of biodiesel due to thermal effects [94]. Free fatty acids are the saturated or unsaturated monocarboxylic acids that occur naturally in fats, oils or greases but are not attached to glycerol backbones. Higher amount of free fatty acids leads to higher acid value. Acid number can provide an indication of the level of lubricant degradation while the fuel is in service [101]. Acid value is expressed as mg KOH required for neutralizing 1 g of oil. Higher acid content can cause severe corrosion in fuel supply system of an engine. Table 6 and Fig. 9 shows acid value of JCME produced, JCME reviewed and three non-edible biodiesel (PPME, RCME and AIME). It can be seen that JCME produced agrees with the limit specified in ASTM D6751 and EN 14214 standards which is below 0.5 mg KOH/g oil. However, the lowest JCME obtained by Rao et al. [60] is 0.01 mg KOH/g oil and RCME has the highest acid value of 1.008 mg KOH/g oil [82,86]. RCME can cause a severe corrosion in fuel supply system CI engines with the high acid value. Therefore, it is recommended that these oils should undergo three-step esterification process to reduce their high acidity before being used in CI diesel engines.

4.7. Iodine value

The iodine value is greatly influences fuel oxidation and deposits formed in diesel engines injectors [94,100,102]. A higher number would imply poorer stability. However, iodine value is a factor influencing the increase or decrease of NO_x emissions. It is reported that decreasing the chain length or increasing the number of double bonds can lead to higher iodine value [69]. Moreover, the maximum limit of iodine value is 120 g I_2/100 g in biodiesel standards [1,4,8,9,16,20,81–83]. Table 6 shows the JCME obtained are in the range of 102.6 g I_2/100 g–109.5 g I_2/100 g. These results were also compared with other JCME as described in Fig. 10. The result

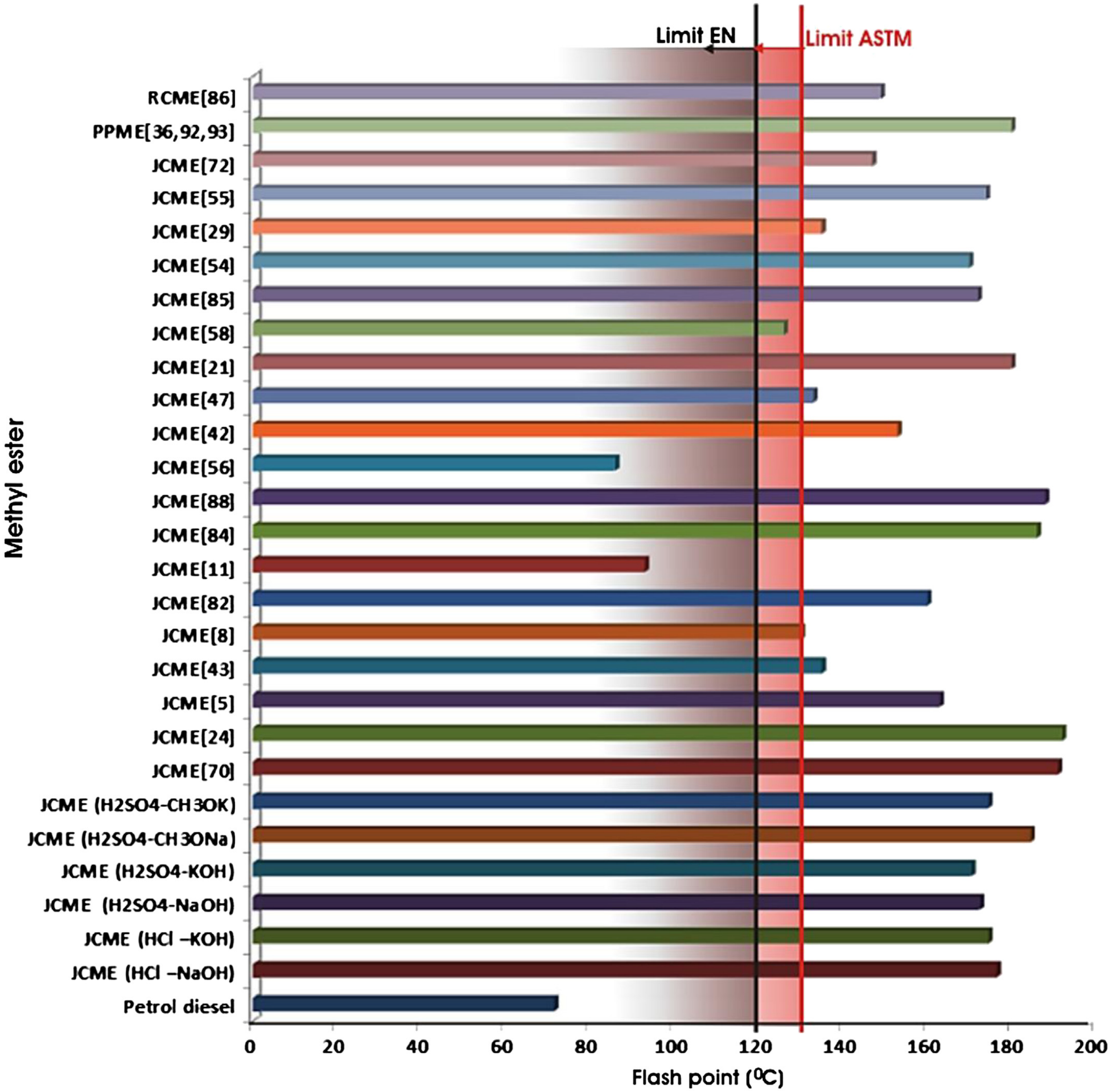


Fig. 6. Flash point of JCME from different homogenous catalysts compared with other JCME, PPME and RCME.

highest iodine value is 109.5 g I_2/100 g from JCME (HCl–NaOH) and the iodine value of PPME is 89 g I_2/100 g [36,92,93].

4.8. Conradson carbon residue

Conradson carbon residue of the fuel is an indication of carbon depositing tendencies of the fuel after combustion. Conradson carbon residue for biodiesel is more important than that in diesel fuel because it shows a high correlation with presence of free fatty acids, glycerides, soaps, polymers, higher unsaturated fatty acids and inorganic impurities [82,97,103,104]. Although this residue is not solely composed of carbon, the term carbon residue is found in all standards because it has long been commonly used. According to ASTM D6751 and EN 14214 standards, the limit of conradson carbon residue is max 0.05%mass and 0.30%mass respectively compared to 0.875%mass for petrol diesel. Table 6 shows the conradson carbon residue content of JCME obtained in this study is in the range of 0.055%mass–0.059%mass. These results were within the range of ASTM D6751 (Max. 0.05%mass) and slightly higher than EN 14214 (Max. 0.03%mass). The other JCME are described in Fig. 11. The result of JCME for all catalyst was slightly higher than other JCME obtained from literature except JCME determined by Acthen et al. [31] and Senthil et al. [105].

4.9. Sulfated ash

Sulfated ash content describes the amount of inorganic contaminants, such as abrasive solids and catalyst residues, and the concentration of soluble metal soaps contained in a fuel sample [33]. Higher level of ash content causes combustion nuisance [98].

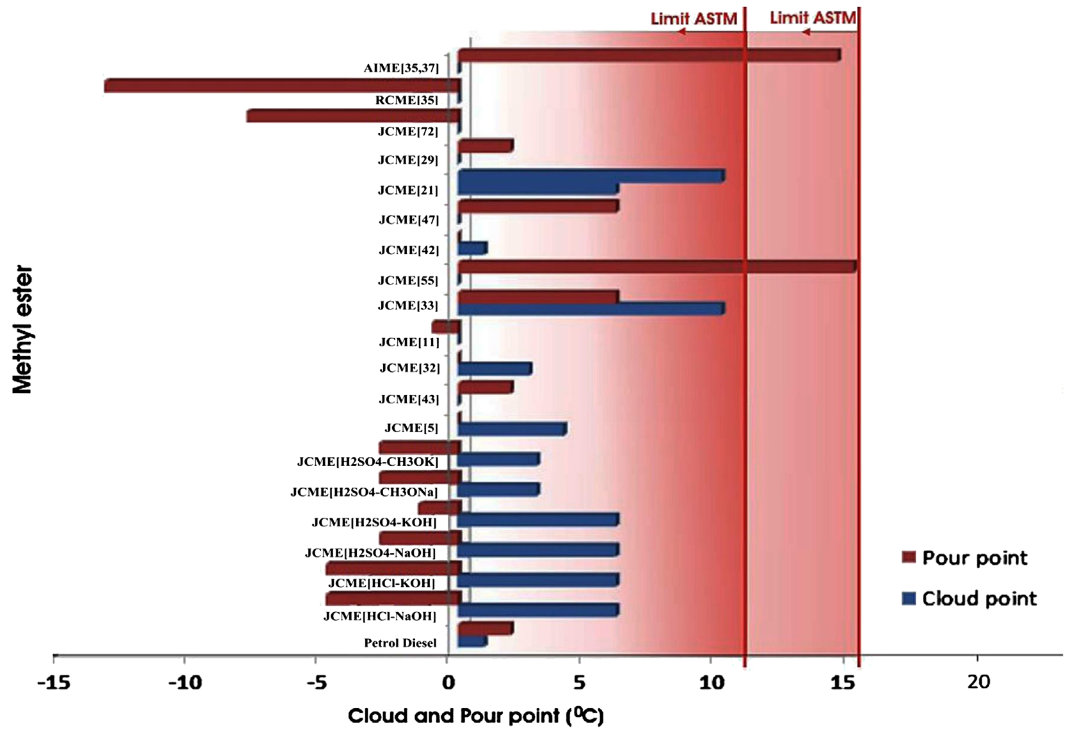


Fig. 7. Cloud point and pour point of JCME from different homogenous catalysts and compare with other JCME, AIME and RCME.

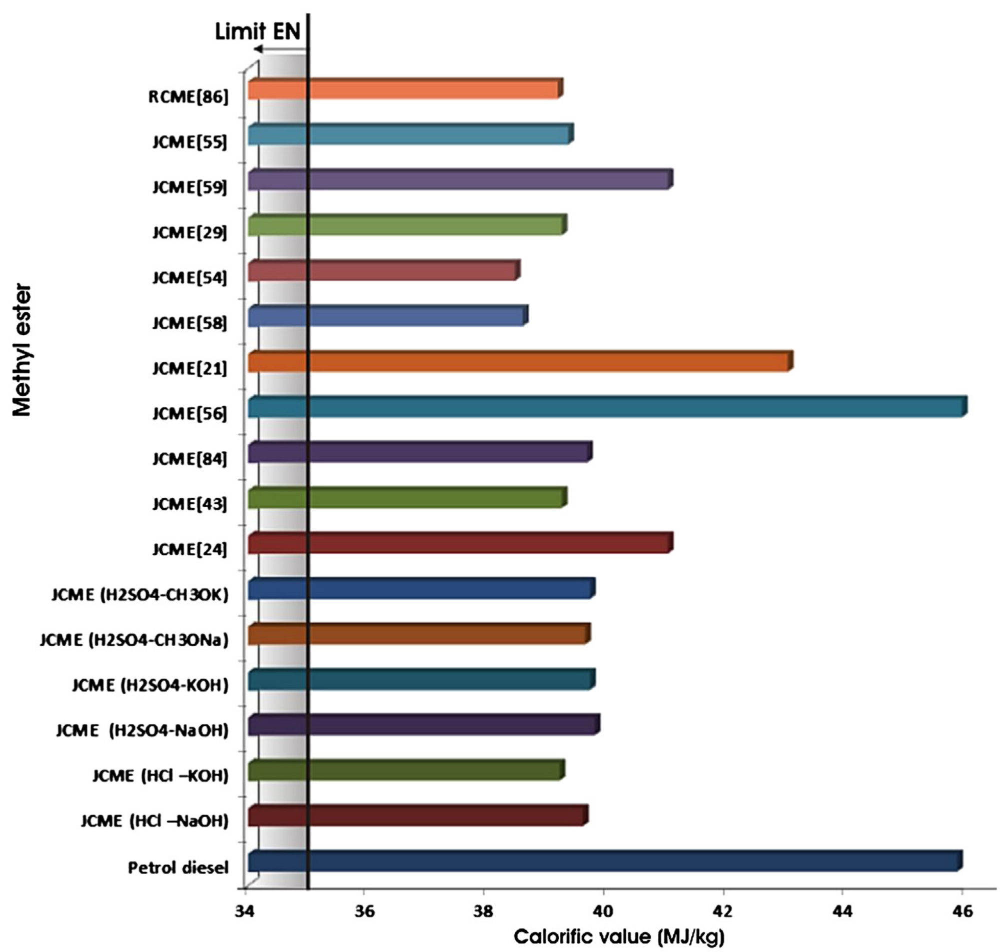


Fig. 8. Calorific value of JCME from different homogenous catalysts compared with other JCME, RCME and AIME.

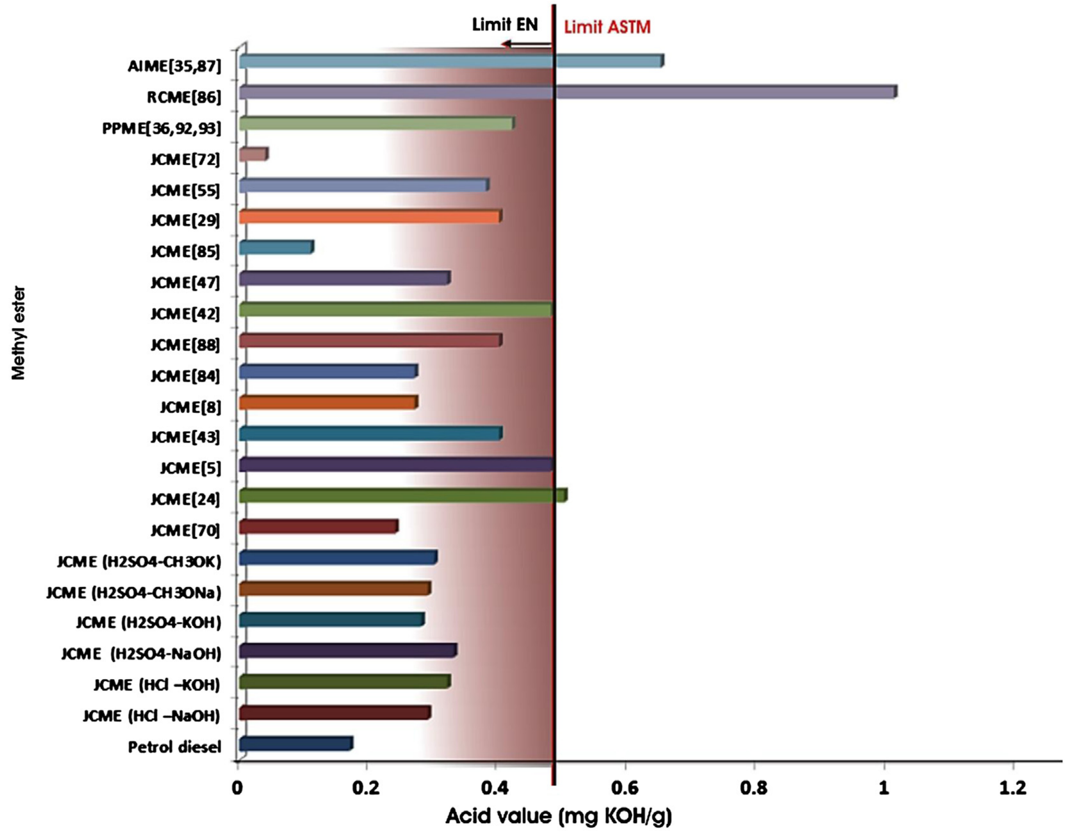


Fig. 9. Acid value of JCME from different homogenous catalysts compared with other JCME, PPME, RCME and AIME.

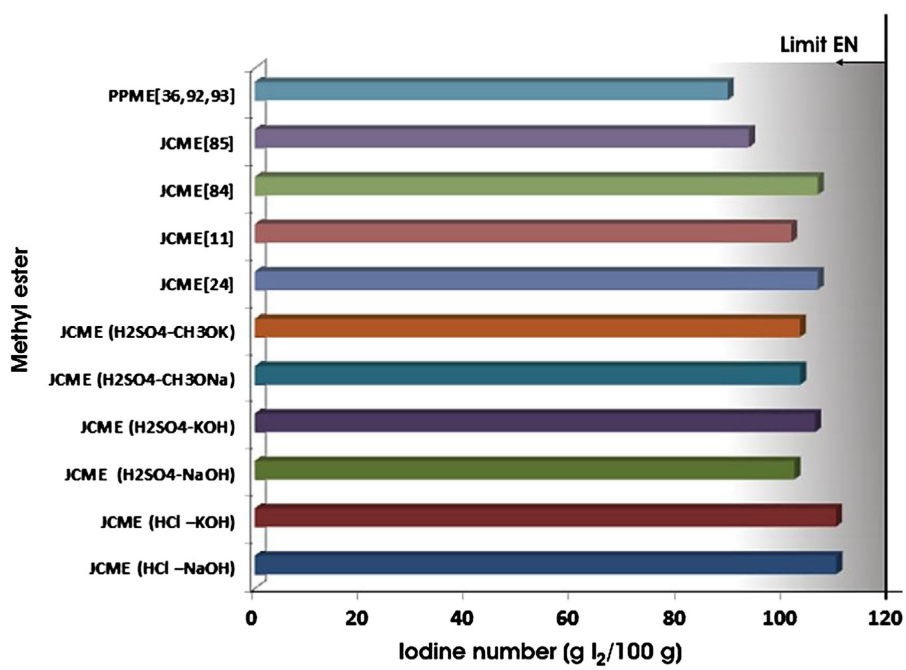


Fig. 10. Iodine value of JCME from different homogenous catalysts compared with other JCME and PPME.

The limit of sulfated ash content prescribed in biodiesel standards is max. 0.02%mass [1,4,8,9,16,20,81–83]. Table 6 shows the sulfated ash of JCME (HCl–NaOH, HCl–KOH) and JCME (H_2SO_4–NaOH, H_2SO_4–KOH, H_2SO_4–CH_3ONa and H_2SO_4–CH_3OK) obtained in this study has the range of 0.004%mass–0.007%mass, respectively. These results were also compared with other JCME and three non-edible biodiesel (PPME, RCME and AIME) are shown in Fig. 12. These values were acceptable according to ASTM D6751 and EN 14214 standards of max. 0.02%mass. There are five higher JCME was mentioned in Table 6 which is obtained from Rashid et al. [88]

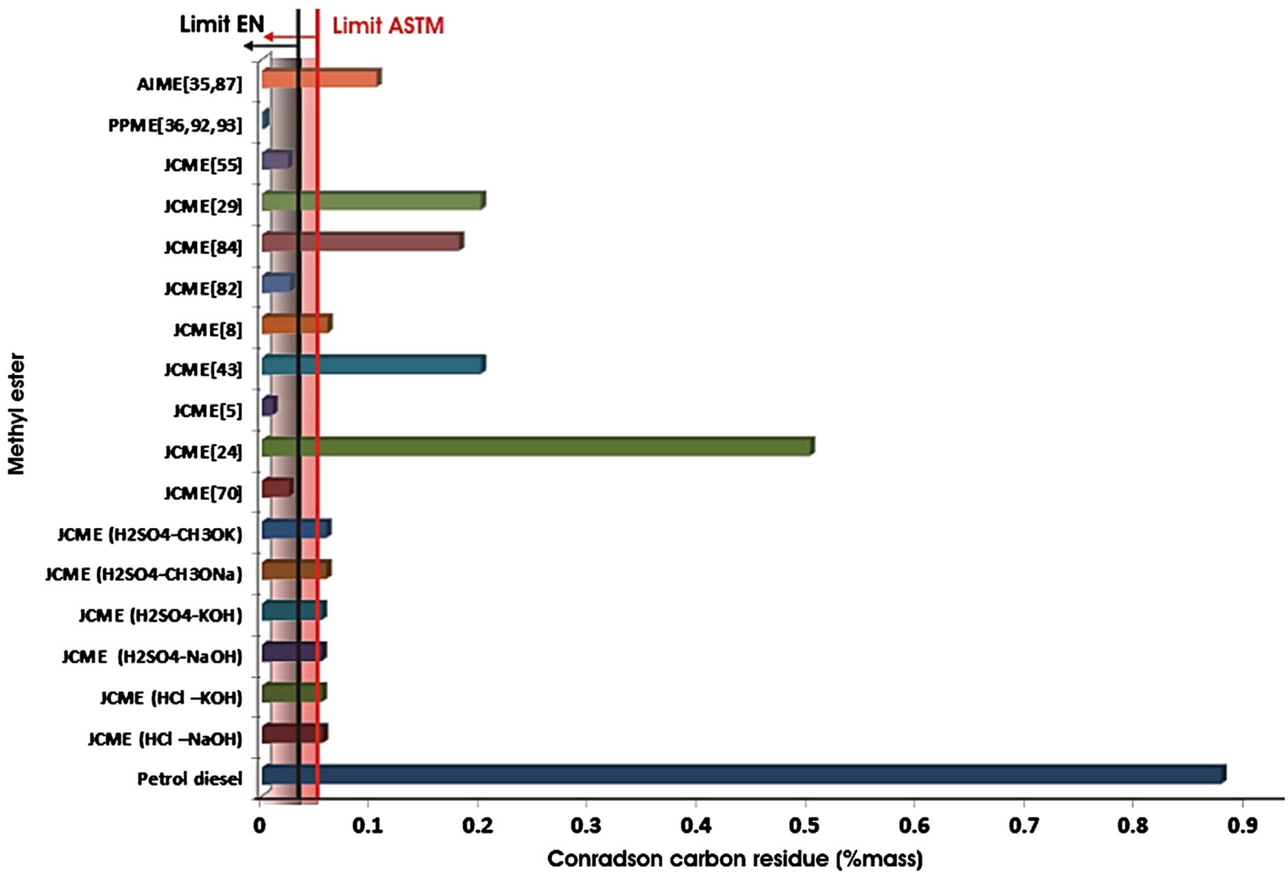


Fig. 11. Condradson carbon residue of JCME from different homogenous catalysts compared with other JCME, PPME, RCME and AIME.

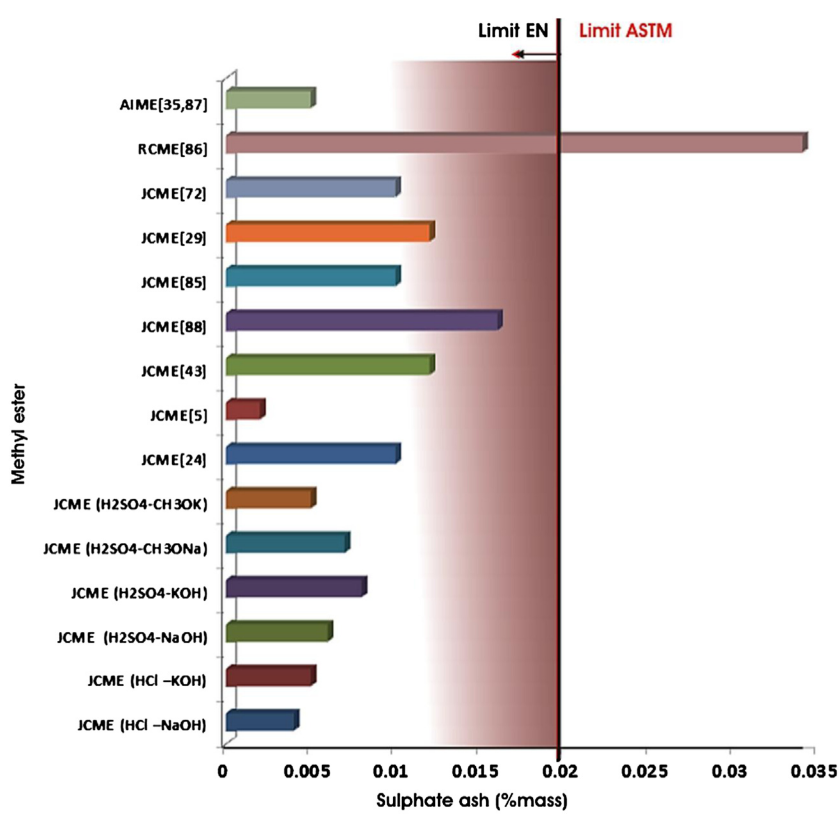


Fig. 12. Sulfated ash of JCME from different homogenous catalysts compared with other JCME, RCME and AIME.

(0.016%mass), followed no [20] (0.013%mass), Parawira [29] and Tiwari et al. [43] and Wang et al. [72] (0.01%mass). While, the lowest sulfated ash is JCME (0%mass) from Qian et al. [42].

5. Biodiesel policy

Several countries have concerns on *jatropha curcas* biodiesel implementation policies and standard [8,15,19,21,106,107]. Khan and el Dessouky [108] reported that *jatropha curcas* as selective raw material for biodiesel production should be exempted from customs duty, income tax and sales tax. The possibility of production of biodiesel from edible oil resources in India is almost impossible. Therefore, prospects of biodiesel from *jatropha curcas* in India have been studied by Jain and Sharma [44]. They reviewed that annual productivity of *jatropha curcas* oil is about 15,000 t and this is indicates that the abundant oil source have been identified as the potential feedstock for biodiesel production. Malaysia is one of the highest biodiesel producers in the word which focused on the development of *jatropha curcas* to discover and evolve feedstock source that may play a great role to change the conventional farming system [4,15]. The development of *jatropha curcas* biodiesel blend was conducted in few countries such as India, China, Indonesia and Malaysia [5,8,28,109]. Thus, the pilot plant scale has setup by institutions or companies for the plantation and production of *jatropha curcas* [8,21,24]. The plantation and production of biodiesel in several countries are presented in Table 7 [8,21,24,110]. *Jatropha curcas* biodiesel seems to be wonder plants which can change renewable energy scenario depend on edible oil based biodiesel such as palm, rapeseed and soy bean oil. However, *jatropha curcas* biodiesel industry still needs government support in tern of financial and policy. Moreover, the biodiesel policy and strategy are very important to maintain the cost of biodiesel and local farmers' direct profitability [111]. The demand of vegetable oil for food has increased tremendously in recent years. It is impossible to justify the use of edible oil as fuel for the purpose of biodiesel production. Moreover, edible oils would be more expensive to be used as fuels. Hence, the contribution of non-edible oils such as *jatropha* curcas will be significant for biodiesel production [112]. The plantation and production of *jatropha curcas* biodiesel as non-edible feedstock can play a vital role in helping developing countries to substitute petrol diesel and reducing the competition of edible oil as fuel and. food for human being. The national biofuel policy will help to spell out a comprehensive framework and concrete initiatives for the use non-edible oil especially *jatropha curcas* to reduce dependency of fossil fuel.

Table 7
The plantation and production of *jatropha curcas* in several countries [8,21,24,110].

No	Location/country	Plantation *jatropha curcas* (ha)	Production *jatropha curcas* biodiesel (ton/year)
1	Indonesia		
	Nanggroe Aceh Darussalam	10,000	16,000
	West Java	6000	9500
	Middle Java	20,000	32,500
	South east Nusa	120,000	203,000
2	China		
	Panzhihua City, Sichuan	120,000	–
	Yuanyang, Yunnan	30,000	–
	Southwestern, Guizhou	40,000	–
	Dongfang, Hainan	–	60,000
	Liuzhou, Guangxi	–	300,000
	Red River basin in Yunnan	2000	–
3	India	9738	–
4	Tanzania	17,600	–
5	Egypt	5000	–
6	Ghana	100	–
7	Madagascar	500,000	–

5.1. Environmental concern on jatropha curcas biodiesel

Biodiesel has become more attractive recently due to its environmental benefits and the fact that it is sustainable and renewable. However, the utilization of *jatropha curcas* biodiesel in engine performance and emission study is still faced with many challenges and difficulties. Several numbers of studies have been done to investigate the effects of *jatropha curcas* biodiesel on exhaust emissions as compared to diesel. Many of these studies have shown (Table 8) that using *jatropha curcas* biodiesel in diesel engines can reduce hydrocarbon (HC), carbon monoxide (CO) and particulate matter (PM) emissions, but nitrogen oxide (NOx) emission may increase [17,59,65,112–116]. According to Chauhan et al. [112] *jatropha curcas* blends reduced 60%, 5%, 75% and 65% of total hydrocarbons, carbon monoxide and particulate matter and smoke opacity respectively compared with petrol diesel fuel. Moreover, *jatropha curcas* biodiesel has higher cetane number (51–52) and 10–11% of oxygen present in biodiesel [60]. Therefore, increasing amount of oxygen in fuel rich combustion is believed to ensure more complete combustion and reducing exhaust emissions [2,4,9,89]. This agrees with the results obtained by Jain and Sharma [44] study which indicated that *jatropha curcas* biodiesel has higher brake thermal efficiency and can reduce exhaust emissions as compared to petrol diesel. However, the disadvantages of biodiesel are high viscosity, low volatility and the reactivity of unsaturated hydrocarbon chains cause poor combustion, formation of deposits and injector cocking in diesel engines [1,3,9,89].

Table 8
Comparative exhaust emissions for *jatropha curcas* biodiesel or its blends relative to petroleum diesel.

No	*Jatropha curcas* biodiesel and its blends	Increased/Decreased % (vs. petrol diesel)				Refs.
		NO_x	CO	CO_2	Others	
1	JCB5, JCB10, JCB20, JCB30 and JCB100	4.8↑↑	5% ↓↓	12% ↑↑	Smoke: 75%↓↓ HC: 60%↓↓	[112]
2	JCB5, JCB10, JCB20, JCB50 and JCB100	12.97%↑↑	15.0% ↓↓ and 23.1% ↓↓	–	Smoke: 54.0%↓↓	[17]
3	JCB20, JCB50 and JCB100	18.19%↑↑	18.48%↑↑	–	Smoke: 44.58%↓↓	[65]
4	JCB50	1%↑↑	–	5%↑↑	–	[59]
5	JCB100	4.4%↓↓–14.5%↓↓	20%↓↓–25%↓↓	–	HC:17% ↓↓–23%↓↓	[113]
6	JCB25, JCB50, JCB75 and JCB100	6↑↑	15.7%↓↓	4%↓↓	Smoke: 9%↓↓	[60]
7	JCB20, JCB40, JCB60, JCB80 and JCB100	7↓↓	–	–	Smoke: 17.5%↓↓	[115]
8	JCB100	25%↓↓	56%↓↓	4.7%↑↑	Smoke: 20%↓↓	[116]

6. Conclusion

In this paper, an investigation of crude *jatropha curcas* oil as a sustainable source for biodiesel has been conducted. Crude *jatropha curcas* oil was extracted using a mechanical expeller and chemically converted to biodiesel via acid catalyst esterification and alkaline catalyst transetrification process. Besides, important properties of JCME such as viscosity, density, flash point, cloud point, pour point, calorific value, acid value, iodine value, condradson carbon residue and sulfate ash have been determined. Moreover, a comparison with the obtained results from several literatures have been done and found that most of the parameters of methyl ester comply with ASTM D6751 and EN 14214 specifications. Based on these results, it is proved that *jatropha curcas* can be utilized as a feedstock for biodiesel.

Jatropha curcas is one of the non-edible oil expanded widely in many countries such as South East Asia (Indonesia, Malaysia and Thailand), India, Pakistan and Africa. Among the various non-edible feedstock, *jatropha curcas* has been found more suitable for biodiesel production and it a substitute for petrol diesel besides edible oil (palm oil and soybean oil). Many researchers were conducted *jatropha curcas* biodiesel production, properties and engine performance/emission characteristic. Therefore, *jatropha curcas* biodiesel has been scientifically proven and can be used to replace petrol diesel in the future.

Acknowledgment

The authors would like to acknowledge for the Ministry of Higher Education of Malaysia and The University of Malaya, Kuala Lumpur, Malaysia for the financial support under UM.C/HIR/MOHE/ENG/06 (D000006-16001).

References

[1] Atabani AE, Silitonga AS, Anjum Badruddin Irfan, Mahlia TMI, Masjuki HH, Mekhilef S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renewable and Sustainable Energy Reviews 2012;16(4):2070–93.

[2] Fazal MA, ASMA Haseeb, Masjuki HH. Biodiesel feasibility study: an evaluation of material compatibility; performance; emission and engine durability. Renewable and Sustainable Energy Reviews 2011;15(2):1314–24.

[3] Jayed MH, Masjuki HH, Kalam MA, Mahlia TMI, Husnawan M, Liaqat AM. Prospects of dedicated biodiesel engine vehicles in Malaysia and Indonesia. Renewable and Sustainable Energy Reviews 2011;15(1):220–35.

[4] Ong HC, Mahlia TMI, Masjuki HH, Norhasyima RS. Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: a review. Renewable and Sustainable Energy Reviews 2011;15(8):3501–15.

[5] Sarin R, Sharma M, Sinharay S, Malhotra RK. Jatropha–Palm biodiesel blends: an optimum mix for Asia. Fuel 2007;86(10–11):1365–71.

[6] Lim S, Teong LK. Recent trends, opportunities and challenges of biodiesel in Malaysia: an overview. Renewable and Sustainable Energy Reviews 2010;14(3):938–54.

[7] Demirbas A. Progress and recent trends in biodiesel fuels. Energy Conversion and Management 2009;50(1):14–34.

[8] Silitonga AS, Atabani AE, Mahlia TMI, Masjuki HH, Badruddin Irfan Anjum, Mekhilef S. A review on prospect of Jatropha curcas for biodiesel in Indonesia. Renewable and Sustainable Energy Reviews 2011;15(8):3733–56.

[9] Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Anjum Badruddin Irfan, et al. Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renewable and Sustainable Energy Reviews 2013;18:211–45.

[10] Balat M, Balat H. Progress in biodiesel processing. Applied Energy 2010;87(6):1815–35.

[11] Balat M. Potential alternatives to edible oils for biodiesel production—a review of current work. Energy Conversion and Management 2011;52(2):1479–92.

[12] Juan JC, Kartika DA, Wu TY, Hin TY. Biodiesel production from jatropha oil by catalytic and non-catalytic approaches: an overview. Bioresource Technology 2011;102(2):452–60.

[13] Xue J, Grift TE, Hansen AC. Effect of biodiesel on engine performances and emissions. Renewable and Sustainable Energy Reviews 2011;15(2):1098–116.

[14] Koh MY, Ghazi TIM. A review of biodiesel production from Jatropha curcas L oil. Renewable and Sustainable Energy Reviews 2011;15(5):2240–51.

[15] Mofijur M, Masjuki HH, Kalam MA, Hazrat MA, Liaqat AM, Shahabuddin M, et al. Prospects of biodiesel from Jatropha in Malaysia. Renewable and Sustainable Energy Reviews 2012;16(7):5007–20.

[16] Singh SP, Singh D. Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review. Renewable and Sustainable Energy Reviews 2010;14(1):200–16.

[17] Tan Pq Hu, Zy Lou, Dg Li Zj. Exhaust emissions from a light-duty diesel engine with Jatropha biodiesel fuel. Energy 2012;39(1):356–62.

[18] Lu H, Liu Y, Zhou H, Yang Y, Chen M, Liang B. Production of biodiesel from Jatropha curcas L. oil. Computers and Chemical Engineering 2009;33(5):1091–6.

[19] Misra RD, Murthy MS. Jatropa—the future fuel of India. Renewable and Sustainable Energy Reviews 2011;15(2):1350–9.

[20] No SY. Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: a review. Renewable and Sustainable Energy Reviews 2011;15(1):131–49.

[21] Yang CY, Fang Z, Bo Li, Long Yf. Review and prospects of Jatropha biodiesel industry in China. Renewable and Sustainable Energy Reviews 2012;16(4):2178–90.

[22] Berchmans HJ, Hirata S. Biodiesel production from crude Jatropha curcas L. seed oil with a high content of free fatty acids. Bioresource Technology 2008;99(6):1716–21.

[23] Kumar A, Sharma S. An evaluation of multipurpose oil seed crop for industrial uses (Jatropha curcas L.): a review. Industrial Crops and Products 2008;28(1):1–10.

[24] Achten W. Sustainability evaluation of biodiesel from Jatropha curcas L. Heverlee, België: Katholieke Universiteit Leuven, Groep Wetenschap & Technologie; 2010.

[25] Heller J. Physic Nut. Jatropha curcas L. Promoting the conservation and use of underutilized and neglected crops. Rome: International Plant Genetic Resources Institute; 1996.

[26] Henning RK. The Jatropha system 2006.

[27] Karmakar A, Karmakar S, Mukherjee S. Properties of various plants and animals feedstocks for biodiesel production. Bioresource Technology 2010;101(19):7201–10.

[28] Hambali E. Prospek pengembangan tanaman jarak pagar untuk biodiesel dan produk turunan lainnya. Indonesia: Bogor; 2006.

[29] Parawira W. Biodiesel production from Jatropha curcas: a review 2010.

[30] Kumar A, Sharma S. Potential non-edible oil resources as biodiesel feedstock: an Indian perspective. Renewable and Sustainable Energy Reviews 2011;15(4):1791–800.

[31] Achten WMJ, Verchot L, Franken YJ, Mathijs E, Singh VP, Aerts R, et al. Jatropha bio-diesel production and use. Biomass and Bioenergy 2008;32(12):1063–84.

[32] Akbar E, Yaakob Z, Kamarudin SK, Ismail M, Salimon J. Characteristic and composition of Jatropha Curcas oil seed from Malaysia and its potential as biodiesel feedstock feedstock. European Journal of Scientific Research 2009;29(3):396–403.

[33] Rashid U, Anwar F, Knothe G. Evaluation of biodiesel obtained from cottonseed oil. Fuel Processing Technology 2009;90(9):1157–63.

[34] Singh He B, Thompson J. Process optimization of biodiesel production using alkaline catalyst. Applied Engineering in Agricultural 2006:22597–600.

[35] World Agroforestry Centre (WAC). Jatropha curcas; 2013.

[36] Pinzi S, Garcia IL, Gimenez FJL, Castro MDL, Dorado G, Dorado MP. The ideal vegetable oil-based biodiesel composition: a review of social, economical and technical implications. Energy and Fuels 2009:232325–41.

[37] Demirbas A. Importance of biodiesel as transportation fuel. Energy Policy 2007;35(9):4661–70.

[38] Pradhan RC, Mishra S, Naik SN, Bhatnagar N, Vijay VK. Oil expression from Jatropha seeds using a screw press expeller. Biosystems engineering 2011;109(2):1–9.

[39] Agarwal D, Agarwal AK. Performance and emissions characteristics of Jatropha oil (preheated and blends) in a direct injection compression ignition engine. Applied Thermal Engineering 2007;27(13):2314–23.

[40] Corro G, Tellez N, Ayala E, Marinez-Ayala A. Two-step biodiesel production from Jatropha curcas crude oil using SiO_2 HFsolid catalyst for FFA esterification step. Fuel 2010;89(10):2815–21.

[41] Zhu H, Wu Z, Chen Y, Zhang P, Duan S, Liu X, et al. Preparation of biodiesel catalyzed by solid super base of calcium oxide and its refining process. Chinese Journal of Catalysis 2006:27391–6.

[42] Qian J, Shi H, Yun Z. Preparation of biodiesel from Jatropha curcas L. oil produced by two-phase solvent extraction. Bioresource Technology 2010;101(18):7025–31.

[43] Tiwari K, Kumar A, Raheman Hifjur A. Biodiesel production from jatropha oil (Jatropha curcas) with high free fatty acids: an optimized process. Biomass and Bioenergy 2007;31(8):569–75.

[44] Jain S, Sharma MP. Prospects of biodiesel from Jatropha in India: a review. Renewable and Sustainable Energy Reviews 2010;14(2):763–71.

[45] Deng X, Fang Z, Liu YH. Ultrasonic transesterification of Jatropha curcas L. oil to biodiesel by a two-step process. Energy Conversion and Management 2010;51(12):2802–7.

[46] Deng X, Fang Z, Liu YH, Yu CL. Production of biodiesel from Jatropha oil catalyzed by nanosized solid basic catalyst. Energy 2011;36(2):777–84.

[47] Kywe TT, Oo MM. Production of biodiesel from Jatropha oil (Jatropha curcas) in pilot plant. World Academy of Science, Engineering and Technology 2009;50:477–83.
[48] Hawash S, Kamal N, Zaher F, Kenawi O, Eldiwani G. Biodiesel fuel from jatropha oil via non-catalytic supercritical methanol transesterification. Fuel 2009;88:3.
[49] Nakpong P, Wootthikanokkhan S. Optimization of biodiesel production from Jatropha curcas L. oil via alkali-catalyzed methanolysis. Journal of Sustainable Energy & Environment 2010:1105–9.
[50] Foidl N, Foidl G, Sanchez M, Mittelbach M, Hackel S. Jatropha curcas L. as a source for the production of biofuel in Nicaragua. Bioresource Technology 1996;58(1):77–82.
[51] Senthil Kumar M, Ramesh A, Nagalingam B. An experimental comparison of methods to use methanol and Jatropha oil in a compression ignition engine. Biomass and Bioenergy 2003;25(3):309–18.
[52] Akintayo ET. Characteristics and composition of Parkia biglobbossa and Jatropha curcas oils and cakes. Bioresource Technology 2004;92(3):307–10.
[53] Baroi C, Yanful EK, Rahman MF, Bergougnou MA. Enviroment friendly biodiesel from jatropha curcas: possibilities and challenges 2010.
[54] Chhetri AB, Tango MS, Budge SM, Watts KC, Islam MR. Non-edible plant oils as new sources for biodiesel production. International Journal of Molecular Sciences 2008;9:169–80.
[55] Ejilah IR, Asere AA, Adisa AB, Ejila A. The effect of diesel fuel-Jatropha curcas oil methyl ester blend on the performance of a variable speed compression ignition engine. Austrailan Journal of Agricultural Engineering (AJAE 2010;1 (3):80–5.
[56] Forson FK, Oduro EK, Hammond-Donkoh E. Performance of jatropha oil blends in a diesel engine. Renewable Energy 2004;29(7):1135–45.
[57] Leung DYC, Wu X, Leung MKH. A review on biodiesel production using catalyzed transesterification. Applied Energy 2010;87(4):1083–95.
[58] Mahanta P, Shrivastava A. Technology development of bio-diesel as an energy alternative. 2011. Available from: 〈http://www.newagepublishers.com/samplechapter/001305.pdf〉.
[59] Rahman KM, Mashud M, Roknuzzaman M, Al Galib A. Biodiesel from Jatropha oil as an alternative fuel for diesel engine. International Journal of Mechanical & Mechatronics (IJMME-IJENS) 2010;10:3.
[60] Rao YVH, Voleti RS, Hariharan VS, Raju AVS, Redd PN. Use of jatropha oil methyl ester and its blends as an alternative fuel in diesel engine. Journal of the Brazil Social of Mechanic Science and Engineering 2009;xxxi(3):253–60.
[61] Supamathanon N, Wittayakun J, Prayoonpokarach S. Properties of Jatropha seed oil from Northeastern Thailand and its transesterification catalyzed by potassium supported on NaY zeolite. Journal of Industrial and Engineering Chemistry 2011;17(2):182–5.
[62] Liu Y, Hl Xin, Yan YJ. Physicochemical properties of stillingia oil: feasibility for biodiesel production by enzyme transesterification. Industrial Crops and Products 2009;30(3):431–6.
[63] Pramanik K. Properties and use of jatropha curcas oil and diesel fuel blends in compression ignition engine. Renewable Energy 2003;28(2):239–48.
[64] Yee KF, Lee KT, Ceccato R, Abdullah AZ. Production of biodiesel from Jatropha curcas L. oil catalyzed by/ZrO_2 catalyst: effect of interaction between process variables. Bioresource Technology 2011;102(5):4285–9.
[65] Sahoo PK, Das LM, Babu MKG, Arora P, Singh VP, Kumar NR, et al. Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. Fuel 2009;88(9):1698–707.
[66] Uriarte FA Jr. Biofuels from Plant Oils; 2010.
[67] Azam MM, Waris A, Nahar NM. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass and Bioenergy 2005;29(4):293–302.
[68] Budiman A, Kusumaningtyas RD, Sutijan R, Purwono S. Second generation of biodiesel production from Indonesian jatropha oil by continuous reactive distillation process. ASEAN Journal of Chemical Engineering 2010;9:2.
[69] Moser BR. Biodiesel production, properties, and feedstocks. In Vitro Cellular & Developmental Biology—Plant 2009;45(3):229–66.
[70] Sudrajat HR. Memproduksi biodiesel jarak pagar (Producing biodiesel from jatropha). Depok, Jakarta, Indonesia: Penebar swadaya; 2006.
[71] Odetoye TE, Ogunniyi DS, Olatunji GA. Preparation and evaluation of jatropha curcas linneaus seed oil alkyd resins. Industrial Crops and Products 2010;32(3):225–30.
[72] Wang R, Hanna MA, Zhou WW, Bhadury PS, Chen Q, Song BA, et al. Production and selected fuel properties of biodiesel from promising non-edible oils: Euphorbia lathyris L., Sapium sebiferum L. and Jatropha curcas L. Bioresource Technology 2011;102(2):1194–9.
[73] El Diwani G, Attia NK, Hawash SI. Development and evaluation of biodiesel fuel and byproducts from jatropha oil. International Journal Environment Science Technology 2009;6(2):219–24.
[74] Verma KC, Gaur AK. Jatropha curcas L.: substitute for conventional energy. World Journal of Agricultural Sciences 2009;5(5):552–6.
[75] Winayanuwattikun P, Kaewpiboon C, Piriyakananon K, Tantong S, Thakernkarnkit W, Chulalaksananukul W, et al. Potential plant oil feedstock for lipase-catalyzed biodiesel production in Thailand. Biomass and Bioenergy 2008;32(12):1279–86.
[76] Jain S, Sharma MP. Oxidation stability of blends of Jatropha biodiesel with diesel. Fuel 2011;90(10):3014–20.
[77] Official Methods and Recommended Practices of the American Oil Chemists Society (AOCS). Acid Value (AOCS Cd 3a-63). third ed.; 1988.
[78] Marchetti JM. A summary of the available technologies for biodiesel production based on a comparison of different feedstock's properties. Process Safety and Environmental Protection 2012;90(3):157–63.
[79] Gerpen JV. Biodiesel processing and production. Fuel Processing Technology 2005;86(10):1097–107.
[80] Ramadhas AS, Jayaraj S, Muraleedharan C. Biodiesel production from high FFA rubber seed oil. Fuel 2005;84(4):335–40.
[81] ASTM. Standard specification for standard specification for biodiesel fuel (B 100) biodiesel fuel (B 100) blend stock for distillate blend stock for distillate fuels; 2011.
[82] Sanford SD, White JM, Shah PS, Wee C, Valverde MA, Meier GR. Feedstock and biodiesel characteristics report; 2011.
[83] The National Biodiesel Board. Specification for biodiesel (B100) – ASTM D6751-09; 2008.
[84] Divakara BN, Upadhyaya HD, Wani SP, Gowda CLL. Biology and genetic improvement of Jatropha curcas L.: a review. Applied Energy 2010;87 (3):732–42.
[85] Becker K, Makkar HPS. Jatropha curcas: a potential source for tomorrow's oil and biodiesel. Lipid Technology 2008;20:5.
[86] Panwar NL, Shrirame HS, Rathore NS, Jindal S, Kurchania AK. Performance evaluation of a diesel engine fueled with methyl ester of castor seed oil. Applied Thermal Engineering 2010;30(2-3):245–9.
[87] Ragit SS, Mohapatra SK, Kundu K, Gill P. Optimization of neem methyl ester from transesterification process and fuel characterization as a diesel substitute. Biomass and Bioenergy 2011;35(3):1138–44.
[88] Rashid U, Anwar F, Jamil A, Bhatti HN. Jatropha Curcas Seed Oil as a Viable Source for Biodiesel. Pakistan Journal Botany 2010;42(1):575–82.
[89] Atadashi IM, Aroua MK, Aziz AA. High quality biodiesel and its diesel engine application: a review. Renewable and Sustainable Energy Reviews 2010;14 (7):1999–2008.
[90] Canakci M, Sanli H. Biodiesel production from various feedstocks and their effects on the fuel properties. Journal of Industrial Microbiology and Biotechnology 2008;35(5):431–41.
[91] Demirbas A. Relationships derived from physical properties of vegetable oil and biodiesel fuels. Fuel 2008;87(8-9):1743–8.
[92] Karmee SK, Chadha A. Preparation of biodiesel from crude oil of Pongamia pinnata. Bioresource Technology 2005;96(13):1425–9.
[93] Sureshkumar K, Velraj R, Ganesan R. Performance and exhaust emission characteristics of a CI engine fueled with Pongamia pinnata methyl ester (PPME) and its blends with diesel. Renewable Energy 2008;33(10):2294–302.
[94] Kaya C, Hamamci C, Baysal A, Akba O, Erdogan S, Saydut A. Methyl ester of peanut (Arachis hypogea L.) seed oil as a potential feedstock for biodiesel production. Renewable Energy 2009;34(5):1257–60.
[95] dos Santos ICF, de Carvalho SHV, Solleti JI, de La Salles WF, de La Salles KTS, Meneghetti SMP. Studies of Terminalia catappa L. oil: characterization and biodiesel production. Bioresource Technology 2008;99(14):6545–9.
[96] de La Salles KTS, Meneghetti SMP, de La Salles WF, Meneghetti MR, dos Santos ICF, da Silva JPV, et al. Characterization of Syagrus coronata (Mart.) Becc. oil and properties of methyl esters for use as biodiesel. Industrial Crops and Products 2010;32(3):51–821.
[97] Murugesan A, Umarani C, Chinnusamy TR, Krishnan M, Subramanian R, Neduzchezhain N. Production and analysis of bio-diesel from non-edible oils —a review. Renewable and Sustainable Energy Reviews 2009;13(4):825–34.
[98] Chakraborty M, Baruah DC, Konwer D. Investigation of terminalia (terminalia belerica Robx) seed oil as prespective biodiesel source for North-East India. Fuel Processing 2009;90(12):1435–41.
[99] Anwar F, Rashid U, Ashraf M, Nadeem M. Okra (Hibiscus esculentus) seed oil for biodiesel production. Applied Energy 2010;87(3):779–85.
[100] Saloua F, Saber C, Hedi Z. Methyl ester of [Maclura pomifera (Rafin.) Schneider] seed oil: biodiesel production and characterization. Bioresource Technology 2010;101(9):3091–6.
[101] Fernando S, Karra P, Hernandez R, Jha SK. Effect of incompletely converted soybean oil on biodiesel quality. Energy 2007;32(5):844–51.
[102] Schinas P, Karavalakis G, Davaris C, Anastopoulos G, Karonis D, Zannikos F, et al. Pumpkin (Cucurbita pepo L.) seed oil as an alternative feedstock for the production of biodiesel in Greece. Biomass and Bioenergy 2009;33(1):44–9.
[103] Masjuki HH. Biofuel engine: a New Challenge. Kuala Lumpur, Malaysia: Department of Mechanical Engineering Univerisity of Malaya; 2010 editor.
[104] Meher LC, Vidya Sagar D, Naik SN. Technical aspects of biodiesel production by transesterification—a review. Renewable and Sustainable Energy Reviews 2006;10(3):248–68.
[105] Senthil KM, Ramesh A, Nagalingam B. An experimental comparison of methods to use methanol and Jatropha oil in a compression ignition engine. Biomass and Bioenergy 2003;25(3):309–18.
[106] Kumar Biswas P, Pohit S. What ails India's biodiesel programme? Energy Policy 2013;52(0):789–96.
[107] Kumar Biswas P, Pohit S, Kumar R. Biodiesel from jatropha: can India meet the 20% blending target? Energy Policy 2010;38(3):1477–84.
[108] Khan NA, el Dessouky H. Prospect of biodiesel in Pakistan. Renewable and Sustainable Energy Reviews 2009;13(6–7):1576–83.
[109] Ayudhaya NLN, Garivait S. Potential of Jatropha curcas derived biodiesel for rice farmers in Thailand. Energy Procedia 2011;9(0):252–63.
[110] Thepkhun P. Biofuels Standard & Regulations in Thailand. 2010. Available from: 〈http://ec.europa.eu/energy/res/events/doc/biofuels/presentation_thai_vs3.pdf〉.
[111] Kumar S, Chaube A, Jain SK. Critical review of jatropha biodiesel promotion policies in India. Energy Policy 2012;41:775–81.

[112] Chauhan BS, Kumar N, Cho HM. A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends. Energy 2012;37(1):616–22.
[113] Huang J, Wang Y, Jb Qin, Roskilly AP. Comparative study of performance and emissions of a diesel engine using Chinese pistache and jatropha biodiesel. Fuel Processing Technology 2010;91(11):1761–7.
[114] Hanumantha Rao YV, Voleti RS, Hariharan VS, Sitarama Raju AV, Nageswara Redd P. Use of Jatropha oil methyl ester and its blends as an alternative fuel in diesel engine. Journal of the Brazilian Society of Mechanical Sciences and Engineering 2009:31253–60.
[115] Sivaprakasam S, Saravanan CG. Optimization of the transesterification process for biodiesel production and use of biodiesel in a compression ignition engine. Energy & Fuels 2007;21(5):2998–3003.
[116] Jindal S, Nandwana BP, Rathore NS. Comparative evaluation of combustion, performance, and emissions of jatropha methyl ester and karanj methyl ester in a direct injection diesel engine. Energy & Fuels 2010;24(3):1565–72.